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ABSTRACT

To document the driving experience of amputees and to test whether amputees differ from non-amputees in the operation of a simulated motor vehicle, related literature was reviewed, a comprehensive study of private motor vehicle operation by amputees was carried out, and 100 persons (20 non-impaired, non-commercial drivers, 20 non-impaired, commercial drivers, and 60 amputees) were tested on a vehicle simulator to study the physical components of steering and braking. In addition, the amputees were interviewed by a psychiatric social worker. The clinical interviews revealed a universal presence of chronic depression among the amputees. The experimental tests indicated that there was no evidence that amputees who were able to pass conventional driver licensing tests have greater accident frequencies than do unimpaired persons. The vehicle simulator experiments revealed that, with appropriate power assists, unilateral orthopedic impairment should not necessarily impair driving performance. On the basis that orthopedically impaired persons usually have a high degree of motivation to succeed as safe drivers, it was recommended that the driving abilities of impaired persons be reappraised according to their overall ability to operate vehicles in interstate commerce. (SB)

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AN EVALUATION OF THE ABILITY OF AMPUTEES TO OPERATE HIGHWAY TRANSPORT EQUIPMENT

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AN EVALUATION OF THE ABILITY OF AMPUTEES TO OPERATE HIGHWAY TRANSPORT EQUIPMENT

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Final Report, RD-592

Vocational Rehabilitation Administration

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Guggenheim Center for Aerospace Health and Safety
Harvard School of Public Health
Boston, Massachusetts

1968

CORRECTION

During the preparation of this report, the minimum requirements for qualifications of drivers under the ICC Motor Carrier Safety Regulations were modified by the addition of paragraph (e) to permit the operation of commercial vehicles by persons with amputations under certain conditions. The minimum requirements are shown below as presently constituted.

291.2 Minimum requirements.

Except as provided in paragraph (e) of this section, no person shall drive, nor shall any motor carrier require or permit any person to drive, any motor vehicle unless such person possesses the following minimum qualifications:

(a) Mental and physical condition. (1) No loss of foot, leg, hand, or arm.

(2) No mental, nervous, organic, or functional disease, likely to interfere with safe driving.

(3) No loss of fingers, impairment of use of foot, leg, fingers, hand or arm, or other structural defect or limitation, likely to interfere with safe driving.

(b) Eyesight. Visual acuity of at least 20/40 (Snellen) in each eye either without glasses or by correction with glasses; form field of vision in the horizontal meridian shall not be less than a total of 140 degrees; ability to distinguish colors red, green, and yellow; drivers requiring correction by glasses shall wear properly prescribed glasses at all times when driving.

(c) Hearing. Hearing shall not be less than 10/20 in the better ear, for conversational tones, without a hearing aid.

(d) Liquor, narcotics, and drugs. Shall not be addicted to the use of narcotics or habit-forming drugs, or the excessive use of alcoholic beverages or liquors.

(e) Waiver of physical requirements. Any person failing to meet the requirements of paragraph (a) (1) or (a) (3) of this section may be permitted to drive a vehicle, other than a vehicle transporting passengers, or a vehicle transporting explosives or other dangerous articles of such type and in such quantity as to require the vehicle to be specifically marked or placarded under the Explosives and Other Dangerous Articles Regulations (49 CFR 177.823) or when operating without cargo under conditions which require the vehicle to be so marked or placarded under the said regulations, if the Director, Bureau of Motor Carrier Safety, finds that a waiver may be granted consistent with safety and the public interest, and grants such a waiver, on the basis of an application meeting all of the following requirements:

(1) The application must be submitted jointly by a person seeking relief to permit him to drive and by a carrier wishing to employ such person as a driver, who both agree to fulfilling all conditions of the waiver;

(2) The application must be accompanied by reports of medical examinations satisfactory to the Director, Bureau of Motor Carrier Safety, and recommendations by at least two medical examiners, at least one of whom shall have been selected and compensated by the carrier. Such reports and recommendations must indicate the opinions of the medical examiners as to the ability of the driver to operate safely a commercial vehicle of the type to be driven by him.

(3) The application shall contain a description, satisfactory to the Director, Bureau of Motor Carrier Safety, of the type, size, and special equipment (if any) of the vehicle or vehicles to be driven, the general area and type of roads to be traversed, the distances and time periods contemplated, the nature of the commodities to be transported and the method of loading and securing them, and the experience (if any) of the applicant in driving vehicles of the type to be driven by him.

(4) The application shall specify agreement by both the person and the carrier that the carrier will file promptly with the Director, Bureau of Motor Carrier Safety, such periodic reports as are required and that such reports will contain complete and truthful information as to the extent of the person's driving activity, any accidents in which he may be involved, and any arrests, suspensions, or convictions in which the person is involved.

(i) If the applicant motor carrier is a corporation, the application shall be signed by a corporation officer and the applicant driver.

(ii) If the applicant motor carrier is a partnership, the application shall be signed by at least one of the partners and the applicant driver.

(iii) If the applicant motor carrier is a sole proprietorship, the application shall be signed by the proprietor and the applicant driver.

(5) The applicants shall agree that the waiver shall authorize driving in interstate commercial service for the applicant carrier only, that any arrests or convictions for violations of laws or ordinances, and any revocation or suspension of driving privileges will be reported to the Director, Bureau of Motor Carrier Safety, immediately on occurrence.

(6) The waiver shall not exceed 2 years and will be renewable, upon submission of a new application, if approved by the Director, Bureau of Motor Carrier Safety.

(7) The waiver may be suspended at any time at the discretion of the Director, Bureau of Motor Carrier Safety, and may be canceled by him after the applicant has been given reasonable opportunity to show cause, it any, why such cancellation should not be made.

(8) A copy of the letter granting the waiver under this section, or a legible photographically reproduced copy thereof, shall be retained in the files of the motor carrier at its principal place of business during the period the driver is in the carrier's employment and 12 months after the termination of the driver's employment.

(9) Every driver granted a waiver under this section shall have in his possession while on duty a copy of the letter granting the waiver or a legible photographically reproduced copy thereof covering himself.

(Sec. 12, 80 Stat. 931; 49 U. S. C. 1651 note)

FOREWORD

As long ago as 1952 the Interstate Commerce Commission passed a regulation (191.2) in regard to the medical qualifications for driving a public conveyance in interstate commerce and these minimum requirements are still in force. This regulation reads as follows: "No person shall drive, nor shall any motor carrier require or permit any person to drive, any motor vehicle unless such person possess the following minimum qualifications: . . . (1) no loss of foot, leg, arm or hand, (2) no mental, nervous, organic, or functional disease, likely to interfere with safe driving, (3) no loss of fingers, impairment of use of foot, leg, fingers, hand or arm, or other structural defect or limitation, likely to interfere with safe driving". Operators of private motor vehicles with amputations are allowed to drive their own cars if they can demonstrate to the licensing authorities that they can drive safely, have adequate prosthetic devices and have installed the proper equipment in their cars. However, they cannot drive in interstate commerce, in any public conveyance, in large or small trucks, or in buses or passenger conveyances for profit.

The Principal Investigator of this study became interested in this problem early in 1961 when the above regulation was widely discussed during Congressional Hearings chaired by Senator John A. Carroll of Colorado. The President's Committee on the Employment of the Physically Handicapped, the Vocational Rehabilitation Administration and other agencies were also interested in this problem concerning the physically handicapped. The rule was brought to the attention of Senator Carroll by the case of Mr. Harold Hunter, a truck driver for the Shupe and Yost Trucking Company of Greely, Colorado. Mr. Hunter lost his left leg in an accident in 1950, while driving a tractor on his father's farm. After recovery he drove a truck for six years without an accident of any kind. When he was finally discovered he lost his job because of Regulation 191.2 of the Interstate Commerce Commission. His appeal for a waiver was denied. Many believed that the ICC regulation was unfair and that gainful employment was being denied to Mr. Hunter as well as to many others with amputations or certain types of physical handicaps. Nevertheless, the ICC is entrusted with protecting the safety of the public and until evidence is presented to the contrary justifying a change in the regulation, it will remain in force.

The Principal Investigator and his colleagues were urged to undertake a study of this problem by those agencies concerned with obtaining a better understanding of the questions involved. This program was made possible through a grant from the Vocational Rehabilitation Administration and with the advice and assistance of its Director of Research, Dr. William M. Usdane. The first step involved a survey of the licensing procedures for the orthopedically impaired driver in the various states. The second step was to review the literature relating to the accident experience of physically handicapped drivers in representative groups. A study was then made of the accident experience of non-commercial drivers in the Commonwealth of

Massachusetts. The names of a random sample of physically handicapped drivers were obtained from the Registry of Motor Vehicles, and a non-disabled control group was selected, similar in regard to age, sex and other relevant items. The comparison revealed that the non-disabled control group had about twice as many accidents and traffic violations as the disabled group. Possibly greater caution and a higher degree of motivation to drive safely accounted for this interesting finding.

The third phase of the program involved the very extensive and difficult task of designing and building a driving simulator in which an experimental analysis could be made of certain hand, arm and foot control movements involved in driving. Once the laboratory equipment had been built and tested for reliability of operation, representative samples of drivers were put through extensive tests. There were four groups of subjects as follows: (1) Non-commercial - non-amputee drivers; (2) Commercial truck drivers - non-amputees; (3) Upper-extremity amputees and (4) Lower-extremity amputees. The analysis of the driving performance of upper-extremity amputees was more extensive than in the case of those with amputations of a lower extremity.

In general, the results showed that the performance of the non-amputee professional truck drivers was superior to the two other groups, as might have been expected. However, the amputees performed as well or better than the non-impaired, non-commercial drivers. The details of the equipment, the various studies carried out, the experimental findings and conclusions are to be found in subsequent pages of this report. A general summary of the entire project may be found on pages 120 to 123 inclusive.

It would be difficult to acknowledge adequately all of those organizations and professional colleagues who contributed to the project in one way or another. It was indeed a cooperative undertaking representing many academic disciplines, points of view, talents and resources. The overall responsibility in constructing the simulator and carrying out the experimental program rested with Dr. Richard G. Domey. Many other members of the staff at the Guggenheim Center participated in one or more phases of the study. James E. Duckworth assisted in reviewing the licensing practices of the various states and the accident experience of physically impaired drivers. Donald Paterson and Thomas J. Crowley played prominent roles in designing and constructing the mechanical features of the simulator. One of our doctoral students at the School of Public Health, Benjamin C. Duggar, working under the guidance of Professor Thomas B. Sheridan of the Massachusetts Institute of Technology, adapted the display and performance measurement techniques for the study. Dr. Duggar supervised the construction of the electronics apparatus built by Gervase R. Tinsley and Pincus Lanner. He also developed the simulator procedures and data reduction techniques as part of a doctoral dissertation dealing with individual differences in continuous control performance tasks involving the upper extremities of the body. The review of the literature on tracking and the functional characteristics of the human upper extremity formed a part of his dissertation. Mrs. Helen Domey, a professional psychiatric social worker, carried out an extensive personal interview with each subject. The anthropometric studies were performed by Dr. Howard W. Stoudt. Most of the above persons were involved for many months with the collection, reduction, and analysis of the data which were processed at the Harvard Computing Center. The Principal Investigator had the responsibility of the integration of the various parts of the study and the preparation of this final report for publication. Grateful acknowledgement is made to Mrs. Inez Tinsley and Miss Toula Coules for the typing of the manuscript in its several revisions.

Excellent cooperation was obtained from many sources in planning and carrying out the study. Among those organizations deserving particular mention and thanks are (1) the Massachusetts Registry of Motor Vehicles, (2) the Boston Regional Office of the Vocational Rehabilitation Administration, (3) the Amputee Veterans' Association of America, Inc., (4) the Amputee Clinic of the Massachusetts General Hospital, (5) the Liberty Mutual Insurance Company Rehabilitation Center, (6) the Massachusetts Rehabilitation Commission, and (7) the Teamsters' Union.

The Research Laboratories, General Motors Corporation, loaned a Chevrolet station wagon for an indefinite period of time for experimental purposes. This enabled us to measure and record driver responses to the steering wheel, and to the brake, clutch and accelerator pedals on a tape recorder in preliminary phases of the project. Certain components of the laboratory simulator were donated by the Chrysler Corporation, Ford Motor Company, International Harvester Company, and Mack Trucks, Inc. Several other companies donated apparatus or other types of equipment too detailed to enumerate here. Other companies donated special equipment for vehicles to be operated by amputees. The project could not have been completed without these generous contributions of equipment because of limited funds for the overall project.

The major financial grant for the project was made to the Harvard School of Public Health by the Vocational Rehabilitation Administration. Additional funds were contributed by the Insurance Institute for Highway Safety, Washington, D.C., and The Research Laboratories, General Motors Corporation, Warren, Michigan.

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I. INTRODUCTION AND STATEMENT OF PROBLEM

A. The Highway Accident Problem and the Orthopedically Impaired Driver

In 1967 as a result of motor vehicle accidents in the United States, 53, 100 people were killed, 1, 900, 000 suffered injuries disabling them beyond the day of the accident, over 160, 000 of whom suffered some degree of permanent impairment. The cost of medical expenses, wage losses, property damage and overhead insurance for these accidents was $10,000,000,000 (National Safety Council, 1967). While it is not the purpose of this study to deal with the overall aspects of the highway safety problem, the above statistics do present the frame of reference within which the problem of the orthopedically handicapped driver must be viewed.

At the present time, increasing attention is being focused on the causes and prevention of highway accidents. As a result, in our society where the citizen assumes the right to drive, questions of qualifications for drivers' licenses have arisen. Subgroups such as the very young and old and those with physical or psychiatric disabilities have been more closely observed. More limitations are being imposed upon their driving privileges than the remainder of the population. Some amputees and the hard-of-hearing are restricted solely because they are handicapped. As a rule, the more difficult the driving task or the more responsibility associated with it the greater the number and magnitude of restrictions.

An example of severe restrictions upon commercial driving by amputees and others with physical impairments is found in Section 191.2 of the Interstate Commerce Act: (there must be) "no loss of foot, leg, fingers, hand or arm, or other structural defects or limitation likely to interfere with safe driving". Although objective evidence supporting these restrictions has been lacking, attempts to modify the law in favor of the physically impaired have been unsuccessful.

To obtain the information needed to make an objective decision about this problem, a series of recommendations for research were made in a Congressional Hearing before House Subcommittee on Interstate and Foreign Commerce on April 23, 1958. Those recommendations most closely related to the topic of commercial driving by the physically handicapped are as follows: 1) Studies should be made to determine specific organic disabilities that limit the ability of individuals to drive safely, and 2) medical data should be collected in accident cases to determine the relationship of physical condition to accident causation. The specific recommendation regarding the orthopedic category of medical disabilities was that, 3) a study should be made of the driving record of veterans with amputations or other orthopedic disabilities who operate specially equipped motor vehicles.

The basic question of allowing the orthopedically impaired to drive in Interstate Commerce can be answered in either of two ways: 1) Permit the physically impaired to drive commercially, collect data on their accident histories, and compare them with the records of similarly exposed, nonphysically impaired drivers, or 2) study a representative sample of physically impaired drivers systematically, prior to modifying the ICC requirements. The latter course of action is recommended, because, with the research skills and techniques now available, it is unnecessary to undertake experimentation on the open highways with the attendant risk to the general driving public.

The size of the population with which we are concerned can be estimated from data gathered in the 1957-58 National Health Survey which indicated that approximately 24 million Americans suffer from some form of physical impairment and that 13 million of them involve some limitation of motion. (U. S. National Health Survey, 1959) More germane to the present project are the estimates of the Eastern Paralyzed Veterans Association: 1) there are about 3 million seriously disabled persons in the United States; and 2) about one million of these drive with some type of special hand- or foot-controls.

B. Objectives of the Present Study

Information on the ability of the physically handicapped to drive motor vehicles is a basic requirement for the clarification of the problems involved in the apparently arbitrary elimination of such drivers from interstate commerce. Although some states have procedures for the physical examination of drivers, adequate criteria for disqualification have not yet been developed. This applies to conditions such as epilepsy, diabetes and heart disease as well as amputees and those with related physical impairments. The Vocational Rehabilitation Administration has been especially concerned with this problem because relatively large numbers of persons may be unfairly deprived of opportunities for employment.

There are two primary aspects in the present investigation. The first is a survey of the literature and an evaluation of the driving experience of amputees. Special attention is given to state licensing procedures for physically handicapped drivers, their accident experiences, and the possible relationships between physical handicaps and motor vehicle accidents.

As part of the initial phase of the investigation, the driving records of known physically handicapped drivers in Massachusetts were systematically surveyed. The variables studied were: 1) type of impairment; 2) frequency of accident; 3) class of accident; 4) other legal citations; and 5) costs. In each case the records of the impaired drivers were matched with those of non-impaired drivers of similar age and sex who had held a driving license for a similar number of years. The results of this phase of the study are reported in Parts II and III, relating the licensing procedures and the accident experience of physically handicapped drivers.

The second major phase of the project involves an experimental analysis of simulated driving performance by the physically impaired. As background, the literature on the functional characteristics of the human upper extremity has been summarized and reviewed with special reference to the steering task. (Part IV) In Part V a description is given of the development of the experimental apparatus (driving simulator) as well as a description of the performance measures.

The adjustment problems of the amputee driver have been studied in diagnostic interviews. The results of these clinical interviews are reported in Part VI in relation to the selection of subjects for the experimental program in this study. Photographs of representative subjects are shown in Figures 20 and 21.

Performance data from a driving related, tracking task have been obtained on three groups of drivers as follows: (1) Twenty non-commercial - non-amputees, (2) Twenty commercial non-amputee drivers, and (3) Sixty amputees. Forty of these amputee drivers, with either upper or lower amputations, took part in an abbreviated experimental schedule. These twenty took the complete testing program as did the twenty subjects in (1) and (2) alone. The amputees in the full experimental program were all subjects with upper extremity amputations as shown in Figure 20. Comparison of the results on the three groups of twenty subjects each are reported in Section VII.

A general discussion and interpretation of the experimental findings may be found in Part VIII, and a concise summary of the entire project is given in Part IX.

The ultimate purpose of this study is to provide objective data to those concerned with the regulation of commercial drivers which may assist them in reaching decisions based upon factual information about the accident experience and driving ability of handicapped compared to non-handicapped drivers.

II. LICENSING PROCEDURES FOR THE ORTHOPEDICALLY HANDICAPPED DRIVER

A. Introduction

During the past few years increasing numbers of orthopedically-handicapped persons have applied for commercial driving privileges. However, such applicants have been barred by the Interstate Commerce Act from this job whenever it includes interstate driving. Since the ability of the amputee to drive commercial vehicles is in question, it has become very important to obtain some objective assessment of their abilities.

The association of accident frequency with physical disabilities seems likely for two reasons. The first is that highway safety as it relates to driving skill depends upon performance; and type and severity of disability are two variables that would be expected to influence performance. The second reason is that the highway transport system itself is a major source of accidents from which permanent, physical impairments derive. Of those persons who sustain permanent impairments through the highway transportation system, a certain number apply for restoration or continuation of their driver licenses.

To see the problem of commercial driving by the physically handicapped clearly, it is necessary to understand the existing climate of opinion and the driver selection regulations. Opposing the Interstate Commerce Act, K. V. Banta, Acting Executive Secretary of the President's Committee for the Employment of the Physically Handicapped, notes that "We do not have information on studies which have been made on amputee driver abilities. . . . The principal problem as we see it, is the handicapped driver restriction in the Interstate Commerce Commission regulation barring all amputees and hard-of-hearing persons from driving any type or size of a truck under their authority. We have evidence of individuals who have very successfully and safely operated commercial vehicles ranging from pick-up trucks to the biggest tractor trailers".

A similar position is taken by Dr. H. W. Glattly, the Executive Secretary of the Committee on Prosthetics Education and Information, National Academy of Sciences-National Research Council. "I am sure you are familiar with the restrictive regulations of the Interstate Commerce Commission that now prohibit an individual with a loss of arm or leg from driving a truck in interstate commerce. Since many states and cities pattern their physical standards for truck drivers upon those of the ICC, these regulations constitute a definite abridgment of employment opportunities for amputees. It was because there is no factual information on this subject that a request was made to your institution to conduct these studies. We believe, that for certain amputation levels, modern prosthetic restoration achieves a degree of functional regain that is compatible with the safe driving of vehicles". It should also be pointed out that power steering, power brakes and other advances should aid the physically handicapped in the safe operation of vehicles.

In a bill submitted before the 2nd Session of the 86th Congress on August 31, 1960, Congressman Williams of Louisiana asked that the Interstate Commerce Act prohibiting amputees from commercial interstate driving be amended as follows: "except that no individual who has suffered the loss of a foot, leg, hand, or arm impairment or loss of hearing shall be prohibited from operating any motor vehicle in interstate or foreign commerce under any rule or regulation of the Commission prescribed under this subparagraph or subparagraph (2), (3), or (3a) of this subsection if such individual has been examined by a doctor of medicine or osteopathy admitted to the practice of medicine or osteopathy in a state, and such doctor determines that such loss or impairment will not prevent such individual from safely operating such vehicle". This bill failed to pass, and although it was reintroduced to the 87th Congress, it failed again.

In addition to the Federal ICC regulation, the various states have either formal regulations or informal rules for licensing handicapped persons. These regulations include commercial licenses, which are generally more restrictive than noncommercial licensing practices. Some states have adopted licensing qualifications similar to those in the Interstate Commerce Act, including the clause prohibiting persons with orthopedic disabilities from driving vehicles. Some, but not all, states permit commercial driving by amputees within their borders. Such licensees must meet certain predetermined specifications. The states in general, however, are somewhat less strict than the ICC.

In the absence of any objective data, both the position of the Interstate Commerce Act and those who oppose it can well be considered as arbitrary. Orthopedic physicians and industrial medical officers have different opinions. The industrial physician appears to be unwilling to license amputees as commercial drivers with few exceptions. For example, in a 1958 Congressional subcommittee on Research Needs in Traffic Safety the Chairman of the Committee on Orthopedic Standards reported: "It is felt that upper extremities must be essentially normal in order to operate commercial or public transportation vehicles. . . . (and) complete normal function of the lower extremities was necessary for the safe operation of commercial and public transportation vehicles".

Further, on 1 October 1958, Dr. B. Dixon Holland, Secretary of the Council on Industrial Health, American Medical Association, stated that "The Council reaffirmed its adherence to the principle that any individual, whatever his condition, should be permitted to perform any job to which his physical, mental, and emotional limitations can be successfully fitted and which he can perform reasonably efficiently, and without endangering the health or safety of others. The calculated risk to the safety of others which has to be taken in the application of this principle, should be only so great. This principle, in the Council's opinion, justifies the ICC prohibition against amputees driving trucks in interstate commerce".

Dr. Harold Brandaleone, Chairman, Committee on Standards for Motor Vehicle Drivers, Industrial Medical Association has published a carefully constructed set of detailed driver qualification standards (Brandaleone, et al, 1957). In this check list distinct differences between qualifications for the operation of privately-owned vehicles and commercial vehicles are found. These criteria refer to a whole range of disabilities of which orthopedic impairment is only one class. In this guide, Dr. Brandaleone specifically states that, with few exceptions, orthopedic disabilities which interfere with function render vehicle operators unacceptable for commercial driving.

These medical recommendations are professional statements which tend to support the ICC regulation. To the extent that the ICC ruling is based on judgments emanating from clinical experience and medical evaluation, it is not wholly arbitrary. Since the scope of public responsibility assumed by the ICC is very great, that the ICC should reflect this view is understandable. Legislative and public opinion appear to support the ICC. However, lack of data regarding this problem is creating a diversity of opinion about commercial driving as an employment opportunity for the physically impaired.

To deal with such questions more systematically documented evidence is needed. To meet this need the present research program was initiated.

B. Results of Agency Survey

Initially, a large number of agencies expected to be concerned in some way with physically handicapped drivers were contacted. Requests to various social and private agencies elicited a small amount of information on the driving of automobiles by the handicapped and no information on commercial driving by them. Similarly, various state and federal public health agencies supplied little or no information on motor vehicle accident experience of the handicapped. The chiefs of the state police agencies were queried, most replied, and their opinions were found to differ rather widely. Of the foreign agencies contacted, the most comprehensive report came from the Svenska Vanforevardens Centralkommittee (SVCK) and the International Society for the Rehabilitation of the Disabled. They reported a limited survey of the problems of disabled drivers in twenty-one countries. It provided information about its disabled drivers and its rehabilitation resources. However, problems associated with commercial driving were not investigated.

State registries of motor vehicles supplied informative and useful information and copies of relevant laws. A wide variety of regulations dealing with physical disabilities were in full or partial operation among the states. But much work must be done before state licensing regulations can be improved and standardized.

To illustrate this diversity, examine the official points of view taken in the states. The Commissioner of Motor Vehicles in New York remarked in a letter of 11 September 1961: "It has been our experience that while some handicapped operators can safely handle passenger cars, the complexity and difficulty of handling the larger vehicles means that far fewer handicapped persons are able to drive them safely. Although we have no detailed records to substantiate this, it has been our general experience in the past that very few handicapped chauffeurs have passed the reexamination for the larger vehicles".

The Chief of Driver Improvement Control for the State of Michigan wrote in a letter of 13 July 1961: "Standards for the operation of the personal vehicles for commercial vehicles are basically the same. We have not found it wise to differentiate between the degree of competency between the operators or chauffeurs because both are equally capable of causing accidents while driving".

The Chief Inspector of the New Jersey Department of Motor Vehicles, in a speech given in 1946, said "We have not adopted, and we do not propose to adopt, any set rule as to whether or not a person so disabled can secure a driver's license. The only criterion is whether or not the applicant can operate a motor vehicle safely. . . . There are, of course, some types of amputations or disabilities for which we have not been able to compensate. For instance, I do not know of any device which will compensate for the amputation of both arms at the shoulder and certainly no means has been found to deal with the problem of seriously impaired vision".

Many states have provisions for licensing the handicapped on an individual basis. For example, a letter from Delaware, 11 July 1961, provided the following information: "In Delaware any physical impediment, which in the opinion of the examiner would tend to make the applicant an unsafe driver is given special consideration. The driver with disabilities must meet the requirements of the road test as well as the individual without disabilities; that is, the disabled applicant will not be given special consideration on the road test since other drivers on the highway who do not know of his disabilities will not do this". If, in the opinion of the Delaware examiner, special equipment is needed to insure the safe operation of a motor vehicle, it is his duty to explain this to the applicant. However, the quality or efficiency of the special equipment is seldom specified. The application for the license is marked to indicate special equipment was recommended, and all restrictions are noted on the driver's license for the information of enforcement agencies. Whenever the department has reason to believe an applicant is physically incompetent or disabled, he is not licensed until he has been examined by competent medical authority and pronounced physically able to drive safely.

Pennsylvania has one precise disqualification: amputation of both hands is an automatic and complete disqualification of any individual for driving. Otherwise the general attitude is that each applicant must be evaluated individually through medical examination and education. Compensatory devices must be used when recommended. "Education" is making the disabled operator aware of the limitations imposed on him by the disability and instruction in the use of compensatory devices.

Mr. W. F. Bench, the Special Officer for the Handicapped, Massachusetts Registry of Motor Vehicles, stated that Massachusetts Registry found that it was impossible to either control or record comparative risk, even through such a crude measure as total miles driven. (1962) The Province of Manitoba attempted to study this problem by requiring persons involved in accidents to estimate yearly mileages. However, the Deputy Registrar stated in a latter (16 August 1961): "After computing the average miles driven of the drivers involved in accidents during one calendar year, we arrived at an estimate which appeared totally unrealistic. We then discussed this matter with the various police forces responsible for this enforcement in the Province, and it was generally agreed that as a rule most drivers reporting accidents had no conception of the mileage they actually drove during the course of a year. The estimates that they would give to the police were so unrealistic that we felt the information was of no significance. As a result of this experience, we were obliged to disregard the accident reporting form". Uncontrolled (limited) studies of the handicapped driver in New Jersey, North Carolina, Connecticut, Wisconsin, Washington, Ontario, Manitoba, and the State Farm Insurance Company of Indiana failed to account for the relative exposures of the drivers.

In summary, the general attitude of the agencies queried seems to be that many orthopedically handicapped persons can drive passenger cars safely. But opinion is sharply divided over issuing commercial driving privileges to the physically impaired.

C. Review of the Literature

Although a preliminary search of the literature revealed a general lack of information on driving by the physically handicapped, nearly 500 items which showed any potential of dealing with some aspect of this problem were ultimately examined. However, a relatively small number of these were found to be actually concerned with the driving problems of the handicapped.

Much has been written about minimum requirements for driving in general, most of which are conservative opinions by medical personnel. For example, the Committee on Medical Aspects of Automobile Injuries and Deaths (1959) of the American Medical Association has suggested various restrictions for licensing of drivers. The medical profession tends to advise that drivers with major amputation deformities may drive their own vehicles if properly fitted and skilled in the use of an adequate prosthetic device or vehicle modification. (National Conference on Medical Aspects of Driver Safety and Driver Licensing, 1964)

Many state registry departments have regulations concerning the licensing of amputees. In a recent paper from the Center for Safety Education of New York University, the licensing rules of 50 states were surveyed. The findings concerning missing or paralyzed limbs, inoperative joints, stature, and strength requirements, reveal a wide variety of legislation with a wide range of acceptability and nonacceptability for driving. Some departments, responding to the questionnaire, listed no provisions for disabled drivers. Fifteen departments listed specific defects and the devices necessary for their correction. Twenty-seven departments had broad regulations which were apparently intended to serve the same purpose as the more specific laws. According to one statement in the study, "perhaps many others also have restrictions but did not report them". (Wagner, 1959) The American Optical Company (1952) has made a survey of state laws covering various aspects of driver licensing. All fifty states and the District of Columbia indicated that there were laws for disqualification of drivers who were "mentally or physically unfit".

The members of a conference of medical persons from several large firms engaged in transportation, such as United Parcel Service, and Greyhound Bus Lines, were nearly unanimous in suggesting that drivers with physical, psychological, or neurological impairments should be disqualified. Safety records within their own companies were given as the basis for these conclusions. (National Safety Congress, 1957) When using records such as these, it should be remembered that the causal factor has not been determined. However, controlled studies have shown that certain psychological characteristics differentiate high accident from low accident groups. No such convincing evidence exists with respect to drivers with orthopedic impairments.

One state has attempted to retest all its licensed drivers as each license becomes due for renewal. The state itself evaluates visual acuity and the use of at least one hand; and the rest is done by any licensed medical doctor at the expense of the applicant. In the first year of study, the medical examinations disqualified 602 of the 422, 000 applicants examined. (Wilbar, 1963) This procedure presents various problems. First of all, the cost and burden upon medical resources can be excessive. In addition, the medical tests are uncontrolled and unstandardized. A person rejected by one doctor could "shop" for another. In order that the system be fair it must be impartial and equitable for all concerned; it must respect both the individual applicant and the public safety.

Brandaleone and Friedman (1956) have published a detailed study of physical standards for vehicle operators, but the only physical amputations mentioned are of fingers or toes. It is implied that more serious amputations need not be considered since such persons should not drive. Dr. Eugene Owen, President of the Northwest Association of Occupational

Physicians, has stated that: "With relation to amputations, there should be no necessity to discuss these conditions as it is evident that one with an amputated extremity should not be issued a driver's certificate". (Owen, 1957) In general, the medical profession tends to agree with the ICC regulation that any major amputation deficiency precludes commercial driving.

In one of the few scientific investigations of this problem, Elkow (1945) set minimum requirements for strength and mobility as a screening device to determine whether any individual was capable of taking a state driver examination. He concluded that disabilities should be "minimal" if the handicapped could be allowed to drive. But it is not known how his requirements were derived or what relationships may exist between the experimental test and actual driving.

During the past 3 or 4 years several investigations have been carried out in the U. S., Sweden, and Great Britain on the influence of various medical conditions on the safety of driving. (Waller, 1965; Herner et al., 1966; Ysander, 1966a; Grattan and Jeffcoate, 1967; Norman, 1968) The major emphasis in these studies has been on disease states and chronic medical conditions, e. g., cardiovascular disease, epilepsy. One Swedish study, however, was directly concerned with drivers having physical disabilities characterized by loss of function in one or more of the extremities, or other parts of the body. (Ysander, 1966b) Of the 494 disabled drivers included in the study, 78 had amputations, chiefly of the right arm or hand, or of the right leg or foot. In comparison with a group of non-disabled drivers, matched for age, sex, and length of time of license, the disabled drivers were found to have a lower frequency of accidents than the non-disabled drivers. Within the group of disabled drivers, however there was a slight suggestion that those with loss of function in either right arm - hand or right leg - foot might be more frequently involved in accidents than those with disabilities involving other extremities. Also, the rates for the amputee group tended to be higher than for those whose loss of function was related to such conditions as poliomyelitis. The differences were small, however, and in view of the size of the sample studied, probably did not reach statistical significance. The authors are not aware of any quantitative studies of simulated driving performance on the part of amputees similar to the one reported below.

In Sweden an official commission has been set up to study the problems of disabled drivers, entitled the Swedish Central Committee for Rehabilitation. It is a state-subsidized coordinating body for the rehabilitation of disabled persons in Sweden, where approximately one person in every ten (if the aged are included) experience difficulty in traffic. A list developed by this group of the ways in which cars must be fitted with mechanical devices in relation to different disablements such as amputations of lower and upper extremities may be found in Torell (1966).

III. ACCIDENT EXPERIENCE OF THE PHYSICALLY HANDICAPPED DRIVER

A. Review of Available Data

The review of the literature related to the licensing procedures for physically handicapped drivers included a search for data on their accident experiences. Without exception, these studies had methodological limitations to their utility. It was not possible to make valid inferences concerning the accident experiences of amputee versus non-amputee drivers.

As an example, the state of Michigan, cooperating with the present study, furnished "the only available information we have on the physical condition of drivers involved in accidents during 1960" presented in Table 1.

Table 1

The Physical Condition of Drivers Involved in Accidents in Michigan During 1960

Physical Condition of Driver	Fatal Accidents State-wide	Fatal Accidents Rural	Fatal Accidents Urban	Fatal & Injury Accidents Rural	Fatal & Injury Accidents Urban
Ill	9	7	2	104	43
Fatigued	9	6	3	315	71
Asleep	22	18	4	562	95
Eyesight defective	7	4	3	76	18
Hearing defective	1	1	0	5	1
One or more extremities missing or defective	1	1	0	17	8
Other defects	1	1	0	130	56
Normal	1, 105	672	433	28, 181	10, 550
Condition not known or not stated	865	650	215	4, 884	1, 570
Total Drivers	2, 020	1, 360	660	34, 274	12, 412

There is no information which could be of assistance in determining the rates occurrence of these events, or the relative exposure to hazard of the persons in each category. Nor is it known if the data are complete. These are typical difficulties encountered in trying to compare the accident histories of amputees and non-amputees.

In a study made in 1961 in New Jersey, 266,949 drivers, or ten percent of the total licensed population, were sampled. Lifetime records for 919 drivers classified by the U. S. Government as handicapped were located. Seven hundred seventy-three had no accidents or summonses on their records. The remaining 146 individuals (about 16%) were involved in 130 accidents and received 101 summonses (excluding any that may have been a consequence of an accident). Exposure is completely uncontrolled. It is not known how many years each individual has been licensed nor how many miles each drives. Comparative data for non-handicapped drivers are not available.

In Wisconsin in 1959, records of 2,002,905 drivers were studied; of them, 1,281 were amputees and paralytics. It was found that 117,262 drivers had been involved in accidents and of these 278 had physical defects. There were 952 non-impaired and 8 impaired drivers in fatal accidents; 33,340 non-impaired and 105 impaired drivers in injury-producing accidents. And there were 82,692 non-impaired and 165 impaired drivers in property-damage accidents. The probability of accident involvement was 1:5 for the impaired group and 1:17 for the non-impaired group. Furthermore, the probability of the accident producing an injury was also greater for the impaired (38 percent versus 29 percent). Thus, these data support the ICA position that impaired drivers should be restricted.

On the other hand, a 1957 study in Manitoba found 19,165 of 326,218 drivers to be involved in accidents. Of the 326,218 there were 918 amputees and 72 paraplegics. Seventeen amputees and 2 paraplegics were in accidents. In other words, 1.8% of the amputees, 2.7% of the paraplegics and 5.9% of all others were involved in accidents. And 17.6% of the amputees, none of the paraplegics and 51.2% of all others were cited for driving violations. Thus, the Manitoba experience appears to reverse the findings from Wisconsin. Until more standardized methods of accident research are developed, such studies of driver subgroups will remain difficult to interpret.

Gart (1959) compared "severely handicapped with able-bodied drivers," and found that amputee drivers of passenger cars had a slightly lower accident rate than the national average. He stated: "A comparison of the six month motor vehicle accident rates of seventy-one severely handicapped drivers with the calculated six month rates for all drivers in the United States during 1957, showed that those of the severely handicapped were lower in every respect". He also administered a driving test to 24 handicapped students and 24 non-handicapped students and found the handicapped slightly superior. However, the conclusions from this study were rejected by several insurance companies because the sample was small.

B. A Study of the Massachusetts Experience

Due to the difficulties encountered in interpreting the results of such studies, it was decided to attempt a controlled study of the motor vehicle accident and violation rates of disabled and non-disabled drivers in one state, Massachusetts, utilizing available public records. In this state 2, 800 physically-handicapped drivers had either a handicapped veteran (V) or handicapped person (HP) motor vehicle registration. The sample was drawn alphabetically from this V and HP population from the Registry of Motor Vehicles files by registry personnel. The non-disabled control group was obtained by including the first person listed in the Registry file following the disabled driver, who was also the same sex and age and who had a valid license for approximately the same number of years. The entire disabled driver population was not studied because the data became repetitive after 625 matched cases had been examined. In this sample 322 drivers had special devices on their cars, but not all of these were for amputations.

In this study 143 drivers of 1250 were involved in one or more recorded violations or accidents. Overall there were 492 matched pairs without incidents, and 133 pairs in which either the disabled or non-disabled or both drivers were cited. Of the latter 133 pairs, there were 39 pairs in which the only disabled were cited, 84 pairs in which the non-disabled were cited, and 10 pairs in which both were cited. Thus, of the 625 disabled drivers studied, 49 (or 1 out of 13) were cited. Ninety-four, or approximately 1:7 non-disabled persons were cited. Hence the non-disabled/disabled ratio was roughly 2:1 in favor of the disabled.

In the non-accident violation category, there were 28 pairs in which only the disabled were cited, and 64 pairs in which only the non-disabled were cited, a ratio of over 2 to 1 in favor of the disabled driver. Speeding was the most common violation in each group, followed by "driving under the influence." Fourteen, or half, of the vehicles operated by 28 physically-impaired men were equipped with driver aids. As a result of these non-accident violations, 29 actions were taken by the Registry of Motor Vehicles on the disabled drivers, including 19 suspensions, 3 revocations, and 2 revocations and suspensions. Action taken against the non-disabled drivers totaled 77, including 51 suspensions, 13 revocations and 3 revocations and suspensions (see Table 2).

In the accident category, there were 11 pairs in which only the disabled were cited, and 20 pairs in which only the non-disabled were cited. As a result of these accidents, there were 11 injuries and one death caused by disabled drivers and 25 injuries and one death caused by non-disabled drivers. Property damage costs for 15 vehicles in the disabled driver accidents were $2, 675 plus or including 3 "total losses," and for 33 vehicles in the non-disabled driver accidents, comparable costs were $7, 145 (see Table 3).

Table 2

Non-Accident Violations, Matched Pairs of Disabled and Non-Disabled Drivers

	Disabled Cited Only (28)		Non-Disabled Cited Only (64)	
	Freq.	No. Drivers	Freq.	No. Drivers
Speed	11	10	24	16
Speed (Warning letter)	5	5	12	12
Driving under influence	9	8	20	19
Allowing improper person to operate	2	2	2	2
Improper operation			4	4
Driving without license	1	1	8	7
Driving after suspension of license			1	1
Operating to endanger	2	2	5	5
Driving uninsured motor vehicle			3	3
Driving unregistered motor vehicle			4	4
Racing	2	2	1	1
Unsatisfied judgment			4	4
False name			1	1
Morals			1	1
Failure to stop at stop sign			1	1
Overloading vehicle			2	2
Illegal parking			1	1
Reckless driving			1	1
Health	2	2		
Unspecified	—	—	1	1
Total	34	32	96	86

Actions Taken by the Registry on the Above Violations

	Disabled Cited Only		Non-Disabled Cited Only	
Registry Action	Freq.	No. Drivers	Freq.	No. Drivers
Suspension of License	19	18	51	32
Warning letter (speed)	5	5	10	10
Revocation of License	3	2	14	14
Both Revocation and Suspension of License	2	2	3	3
Total	29	27	78	59

Table 3

Accidents Occurring in Matched Pairs of Disabled and Non-Disabled Drivers

	Disabled Cited Only (11)		Non-Disabled Cited Only (20)	
	Freq.	No. Drivers	Freq.	No. Drivers
Rear-end collision	3	3		
Right angle collision	2	2	6	6*
Fixed object collision	5	5	9	9*
Pedestrian	1	1	1	1
Sideswipe collision			4	4
Head-on collision				
Total	11	11	21	21

Injuries	No. injuries	No. accidents	No. injuries	No. accidents
Self	4	4	15	15
Passenger in disabled driver's vehicle	3	2		
Non-Disabled driver	2	2		
Passenger in Non-disabled driver's vehicle				
Pedestrian	1	1		
Other	1	1		
Passenger in control driver's vehicle			3	2
Other Driver			6	6
Passenger in other driver's vehicle			1	1
Total	11	10	25	24

Deaths	Disabled	Non-Disabled
Pedestrian	1	1

Property Damage Costs	Disabled		Non-Disabled	
	Cost	Frequency	Cost	Frequency
Disabled driver's vehicle	$1575 and 3 total losses	10		
Control driver's vehicle			$4515	20
Other vehicle	$ 950	4	$2490	11
Other property, not vehicle	$ 150	1	$ 140	2
	$2675 & 3 totals	15	$7145	33

*One driver involved in two separate accidents.

The drivers involved in the accidents listed in Table 3 had additional non-accident violations as follows: for the disabled drivers, 14 violations, and for the non-disabled drivers, 32 violations. For the disabled drivers, improper operation and driving under the influence was the most common violation, while for the non-disabled, driving under the influence and operating to endanger were the most common. These drivers had the following actions taken against them by the Registry of Motor Vehicles. The 11 disabled drivers suffered 8 suspensions and 3 revocations, while the 20 non-disabled drivers had 11 suspensions, 9 revocations, 1 continued revocation and 2 revocations and suspensions (see Table 4).

In addition, there were 10 matched pairs in which both the disabled and non-disabled drivers were cited either for accidents or for non-accident violations. Of these, the 10 non-disabled drivers had 10 violations and one accident involving 2 injuries and $450 in property damage. Six of the vehicles of the disabled drivers were equipped with special devices. The 10 non-disabled drivers in these matched pairs were involved in 11 violations and 2 accidents, resulting in one injury and $175 in property damage. These drivers had the following actions taken against them by the Registry of Motor Vehicles: for the disabled drivers 6 suspensions and 1 revocation and 9 suspensions and 1 revocation for the non-disabled drivers (see Table 5).

The data do show a decidedly lower absolute rate of involvement of V and HP disabled drivers versus their non-disabled counterparts if relative hazard criteria are ignored. The ratio is approximately 2:1; that is, the non-disabled control group drivers sustained almost twice as many accidents and were charged with about twice as many non-accident violations as the disabled. This ratio appeared to remain constant regardless of the variable considered.

Some difficulties must be kept in mind in assessing these results. First of all, driver exposure records were not maintained by the Registry; secondly the reliability of the data is unknown. The research supervisor could not directly control the data collection process since only authorized registry personnel have access to official files. It was impossible to determine the reliability of the original registry records; moreover, it has not been necessary to report accidents in which property damage to each vehicle was less than $200.00 and no one was injured. An unknown group of disabled persons have been driving in Massachusetts with standard, rather than V or HP, registrations and were not sampled. Their frequency could not be estimated, nor could these registrants be located in the files without handsorting more than 3 million individual records.

Therefore, the collected data only represent (special) V and HP registrants operating passenger vehicles, not commercial vehicles. Because commercial vehicles are often larger and more complex, commercial driving is physically and mentally more demanding. These limitations imposed upon the study must be considered in any interpretation and evaluation of the data.

Table 4

Non-Accident Violations Occurring to the Disabled and Non-Disabled Drivers Experiencing Accidents

	Disabled Cited Only (11)		Non-Disabled Cited Only (20)	
	Freq.	No. Drivers	Freq.	No. Drivers
Speed	2	2	2	2
Improper operation	4	4	1	1
Driving under influence	4	4	11	9
Driving after suspension of license	1	1		
Operating to endanger	1	1	12	12
Leaving scene of accident	1	1	2	2
Unsatisfied judgment	1	1		
Driving without license			1	1
Driving unregistered motor vehicle			1	1
Driving after revocation of license			2	2
Total	14	14	32	30

Actions Taken by the Registry on the Above Violations and on the Accidents Listed in Table 3

	Disabled		Non-Disabled	
Registry Action	Freq.	No. Drivers	Freq.	No. Drivers
Suspension of license	8	8	11	9
Revocation of license	3	3	9	8
Continue revocation of license			1	1
Both revocation and suspension of license			1	1
Total	11	11	22	19

Table 5

Non-Accident Violations and Accidents Occurring to Both Members of Matched Pairs of Disabled and Non-Disabled Drivers

	Disabled (10)		Non-Disabled (10)	
Violation	Freq.	No. Drivers	Freq.	No. Drivers
Health	3	3		
Allowing improper person to operate	1	1		
Prison sentence	1	1		
Speed	3	3	6	6
Driving under influence	1	1	1	1
Failure to stop at stop sign (warning)	1	1		
Speed (warning letter)			2	2
Admitted to Mental Hospital			1	1
False statement			1	1
Total	10	10	11	11
Accidents				
Right angle collision	1	1	1	1
Pedestrian			1	1
Total	1	1	2	2
Injuries Resulting from Accidents				
Self	1	1		
Non-Disabled Driver	1	1		
Pedestrian			1	1
Total	2	2	1	1

Property Damage Costs	Disabled		Non-Disabled	
	Cost	Freq.	Cost	Freq.
Disabled driver's vehicle	$150	1		
Control driver's vehicle			$ 25	1
Other vehicle	$300	1	$150	1
Total	$450	2	$175	2
Registry Action				
Warning letter (speed)			2	2
Suspension of license	6	6	9	7
Revocation of license	1	1	1	1
Total	7	7	12	10

C. Summary

The operating records of 625 pairs of drivers in Massachusetts were compared on the basis of whether or not they were involved in either highway accidents or non-accident violations. Each pair consisted of a disabled and non-disabled driver. They were matched for sex, age, and number of years of driving. Of the 625 matched pairs: (1) 492 pairs drove without incidents, (2) 39 pairs involved only the disabled driver in a recorded violation or accident, (3) 84 pairs cited only the non-disabled driver and, (4) 10 pairs involved both drivers.

In the category of non-accident violations, 28 pairs involved only the disabled driver and 64 pairs involved only the non-disabled driver. Speeding was the most common violation followed by "driving under the influence". The Registry of Motor Vehicles took 29 punitive actions against 27 disabled drivers and 78 actions against 59 non-disabled drivers.

In the accident category, 11 pairs involved only the disabled driver while 20 pairs involved only the non-disabled driver. The disabled drivers were involved in 11 injuries and one death while the non-disabled drivers were involved in 25 injuries and one death. Property damage was much higher for the non-disabled than for the disabled driver. In this category 11 punitive actions were taken against 11 disabled drivers while 22 actions were taken against 19 non-disabled drivers.

Of the 10 pairs which cited both the disabled and non-disabled driver either for accidents or non-accident violations, the disabled drivers were involved in 10 violations and 1 personal injury accident while non-disabled drivers were involved in 11 violations and 2 accidents. The Registry took a total of 7 actions against 7 disabled drivers and 12 actions against 10 non-disabled drivers.

The data showed a markedly lower ratio of involvement in violations and accidents by the disable drivers as compared to the non-disabled ones. The ratio was approximately 2:1; that is, the non-disabled control group were involved in about twice as many accidents and non-accident traffic violations as the disabled group.

One of the limitations in interpreting these results is that the subjects were not equated for exposure. That is, the number of miles driven and the conditions under which they drove such as time of day, weather, etc., were not reported. Also, some drivers not reported as disabled with the Registry of Motor Vehicles may actually have been so impaired. The above limitations should be considered in any interpretation and evaluation of the study.

IV. A REVIEW OF THE LITERATURE RELATED TO SELECTED AREAS OF PERFORMANCE

A. Functional Characteristics of the Human Upper Extremity

In this section a review is presented of the literature relating to the properties of the human upper extremity which may be expected to influence ability to use a steering wheel. Due to the complexity of the shoulder-arm system, detailed descriptions of the anatomy of the various bones, joints, and muscles will not be given. The emphasis in the survey is directed toward the application and control of force, the primary output of the limbs and the various constraints which limit or distort this output. The interested reader will find the functional anatomy of the upper extremity reviewed in detail in a kinesiology text by Duvall (1959) and in a summary of this subject by Taylor (1955).

The human upper extremity has great mobility. A large number of skeletal parts (32 bones in the shoulder girdle, arm, and hand), are interconnected by a muscular system requiring a high degree of coordination to perform even commonplace movements or applications of force. Motion of the arm depends on the position and movement of the shoulder girdle and trunk and requires fixation or movement of the skeletal parts specific to the movement to be executed. Similarly, movement of the hand and wrist depends on the position and movement of the arm. The flexibility of this limb system requires a wide choice of alternative muscle groups to participate in most (gross) movements or applications of force. However this mobility is achieved at the sacrifice of maximum stability. For most purposes, reduction in stability, compared to that of the postural supporting systems, is of little consequence. However, due to the inherent unsteadiness or tremor in the unsupported upper-extremity, very precise and delicate manipulations may deteriorate.

This literature review of the functional characteristics of the upper extremity will be divided into the following areas: 1) the range of motion and static force, 2) the dynamic characteristics of the arm (reaction time, output and input impedance, power transfer, and speed of motions), and 3) operational considerations (sensitivity and accuracy, proprioception, interaction of movements, and muscular fatigue).

1. Range of Motion and Strength

The shoulder-arm-hand complex is roughly analogous to a four-lever system. These levers rotate on four centers in such a manner as to describe a total of 9 rotational angles. The range of movements and maximum torques developed about the joint axes as reported by Taylor (1955) and by Taylor and Schwarz (1955) are summarized in Table 6. These observations represent average ranges of movement and peak torques exerted by large groups of subjects, and should not be

Table 6

Range of Simple Movements and Maximum Torques about the Joint Axes of the Upper Extremity (from Taylor, 1955, and Taylor and Schwarz, 1955)

Joint Motion	Action	Range (deg.)	Torque (lb. in.)	Conditions
Shoulder	Elevation	40	—	Movements measured as angular displacement about sterno clavicular joint starting from relaxed anatomic position
	Depression	10	—	
	Flexion	20	—	
	Extension	15		
Arm on shoulder	Flexion	180	470	Subjects reclining with arm at side, 6 in. lever arm assumed for torque computation
	Extension	60	470	
	Elevation	180	—	
	Depression	20	—	
	Medial rotation	90	—	
	Lateral rotation	20	—	
Forearm on elbow	Flexion	140	420	Flexion-extension torques measured with subjects reclining and forearm flexed 75 deg. Rotation torques measured at wrist cuffs, subjects standing
	Extension	0	280	
	Pronation	90	110	
	Supination	80	115	
Hand on wrist	Volar flexion	44	200	Torques measured at the metacarpophalangeal line with hand axial to the forearm and subjects seated
	Dorsal flexion	78	135	
	Ulnar flexion	28	150	
	Radial flexion	17	120	

used to predict individual characteristics. On the other hand, torque data, moments of inertia, and movement paths of the segments can be used to estimate maximum rates of acceleration of the unloaded limb.

Glanville and Kreezer (1937) compared the maximum amplitudes for voluntary and passive movements in a group of ten right-handed male adults 20-40 years old, five feet four inches to six feet one inch tall, 120-172 pounds weight. Large individual differences were observed in both the voluntary and passive limits of motion. With the exception of pronation and supination of the forearm the individual differences in voluntary arm movements generally exceeded those for passive movements. In addition, Glanville and Kreezer reported measurements of the velocity of forearm flexion and extension. The velocity measurements were conducted with the forearm and elbow suspended so as to avoid the effects of gravity, but free to move in the horizontal plane. Flexion and extension velocities were measured while the included angle between the upper and lower arm ranged from 15^o-90^o. A portion of Glanville's and Kreezer's data appear in Table 7.

Provins (1955a, 1955b) studied the forces which could be applied to a steering wheel as a function of joint angle and the direction of movement about the joint. Provins' findings can be summarized as follows:

1. Movement about the shoulder joint can produce about 1.5 times as much torque and can maintain this torque three times as long as that produced by movement about the elbow.

2. The amount of shoulder flexion (between 0^o and 90^o) has no significant effect on maximum available torque which may be exerted about the shoulder joint.

3. Amount of torque produced by elbow flexion or extension depends on the angle between the upper arm and forearm, with a maximum produced at an angle somewhat greater than 90^o.

4. Maximum torque developed during elbow flexion is about 40% greater than during extension. For the shoulder, extension is about 15% more powerful than flexion.

Table 7

Maximum Amplitude and Velocity of Voluntary and Passive Movements of the Upper Extremity (from Glanville and Kreezer, 1937)

Movement measurements for mean, lower limit (LL), and upper limit (UL) in degrees, mean value is average for right and left sides

	Voluntary			Passive		
Movement	Mean	LL	UL	Mean	LL	UL
Upper Arm						
Flex (forward)	179.4	164.3	191.0	185.0	172.3	195.3
Extend (back)	57.6	33.6	75.0	69.0	51.0	93.3
Abduct	129.8	112.6	154.3	137.0	116.0	163.0
Rotation (in)	97.0	59.0	130.6	104.6	65.6	135.0
Rotation (out)	83.1	47.6	109.3	92.1	61.3	115.0
Forearm						
Flex	141.2	125.6	156.3	145.6	129.3	157.6
Pronate	92.0	59.0	139.0	108.0	75.6	145.0
Supinate	100.0	74.0	114.3	115.2	92.6	141.6

Velocity of Forearm Movement (degrees per millisecond)

	Mean	LL	UL
Flex	0.434	0.212	0.683
Extend	0.474	0.304	0.823

Provins also noted large individual variations among his group of 12 subjects (8 male, 4 female, 16-33 years of age). Volume of the limb or limb segments did not correlate significantly with strength; however, sample size limits the generality of this observation. The summed torques of both sides of the subjects were essentially equal for both clockwise and counterclockwise rotation of the steering wheel. Two hand performance compared with the sum of the torque produced by the two sides taken separately were found to agree within about 7%.

Provins and Salter (1955) compared maximum torques exerted about the elbow joint when the subject either gripped a wooden handle or pressed against a wrist cuff. The degree of pronation - supination of the forearm was found to affect the torque measurements using the handles, but forearm position had negligible effect on the cuff measurements. Consequently, Provins and Salter concluded that gripping the measuring device may be a limiting factor in strength measurements and that degree of forearm rotation has negligible effect on available torque about the elbow joint.

Arm strength and selected body dimensions of a group of 75 young adult males were measured by Roberts, Provins, and Morton (1955). Strength measurements were expressed as torque about the elbow joint, confounding available force and arm length. With the elbow at a right angle to the upper arm, mean flexion torque was 0.33 lb. in. (SD = .0475), and mean extension torque was 0.281 lb. in. (SD = .0497). Correlation coefficients were computed for strength and several anthropometric measures. Multiple correlations as high as 0.76 (forearm girth, stature, and weight versus elbow extension torque) were obtained. Although the strength of limb may be related to body size, the relation of body size and limb dimensions, especially arm girth, to arm strength was clearly established.

Ross (1957) evaluated the vertical forces which can be exerted on the arm at different distances in front of the shoulder and explained these in terms of a lever system. Ross noted that the available force decreased in an approximately linear fashion as the horizontal distance from the body increases. The slope of this function depends on the elevation of the point of force application relative to the shoulder joint; it becomes smaller as elevation falls below shoulder level. At a distance of nine inches below shoulder level, distance from the body has no effect on maximum force. At any given distance from the body, maximum force can be expressed as a curvilinear function of elevation. Agreement between the theoretical and measured forces is good for moderate to large amounts of elbow and shoulder flexion.

The static forces which could be exerted in several directions as a function of degree of elbow flexion were measured by Hunsicker (1955). The experimental subjects were a group of 55 university students have a mean age of 20.1 years, mean height of 69.9 inches, and mean weight of

162.5 pounds. Subjects were selected to include a broad range of anthropometric characteristics, but distributed in a manner similar to distribution of military aircraft crew body-types. Even with this select sample, the variance in human strength was large. Hunsicker found that it "was not uncommon for one individual to exert ten times as much strength as another man." /Some of Hunsicker's measurements appear in Table 8. The best over-all performance was obtained at 120° flexion, comparable to Provins' results./ Hunsicker also reviewed the literature on static strength and concluded that testing several of the larger muscle groups of the body would provide a good, over-all picture of an individual's strength. Static strength was reported to be poorly correlated with gross body size, but predictable from a combination of size and body build or a combination of body size and specific limb dimensions.

b. Dynamic Characteristics of the Arm

Reaction Time

The dynamic characteristics of the arm which may influence continuous control performance include reaction time (RT), output impedance (force-velocity relationship and its effect on power transfer and speed of motion), and input impedance. With the exception of RT, these characteristics have not been extensively investigated and their importance in tracking performance has not been experimentally verified.

The interval between presentation of a stimulus and either onset or completion of a response has been shown to depend on a variety of factors. Klemmer (1957) varied the foreperiod between a warning signal and the visual stimulus and found a marked dependence of RT on both the foreperiod and on the individual's ability to estimate periods of time. Hick (1951) conducted an experiment in which the number (N) of equally probably stimuli and associated responses were varied. RT was found to be linearly related to the logarithm of (N + 1), beginning at 0.2 seconds for a single-choice-stimulus response. Hick further concluded that in tracking the stimulus can only be to the right or to the left, and RT should be 0.3 seconds. For simple RT experiments, Seashore (1951) reported a high correlation between the responses made by either side of the body. However, as the amount of movement associated with the response increased, the correlation was reduced significantly. Henry (1961) measured the time to begin and complete a horizontal swing of the arm through a 90° arc in response to a stimulus. Data obtained from 120 subjects showed a significant correlation between RT and movement time. Complex stimulus-response combinations, including those which were "unnatural" or different from those encountered in everyday experience, were investigated by Fitts and Seeger (1953). RT was found to depend on the entire ensemble of stimulus-response combinations available, rather than just the particular combination occurring for any given trial. A large amount of learning occurred over a thirty-two day period was also observed, reducing the average RT 30 to 50 percent from initial

Table 8

Static Strength as a Function of Forearm Flexion, Mean of Left and Right Arm (from Hunsicker, 1955)

Condition		Strength (pounds) at various elbow angles				
		180°	150°	120°	90°	60°
1. Pull, sitting, forearm horizontal	Max	184	204	170	160	126
	Median	122	123	102	86	62
	Min	28	26	23	15	15
2. Push, sitting, forearm horizontal	Max	215	210	212	184	177
	Median	135	118	95	82	86
	Min	55	55	55	55	54
3. Lift, sitting, forearm horizontal	Max	103	140	135	110	92
	Median	34	46	52	51	43
	Min	6	10	10	8	9
4. Push down, sitting, forearm horizontal	Max	102	87	122	101	92
	Median	35	40	50	47	47
	Min	12	14	18	13	12
5. Abudction, sitting, forearm horizontal	Max	134	108	90	98	88
	Median	25	25	26	29	32
	Min	8	8	9	10	12
6. Abduction, sitting, forearm horizontal	Max	125	118	120	112	96
	Median	39	42	44	44	50
	Min	13	15	16	12	12

values. The above investigations indicate that there are difficulties inherent in comparing RT values reported in different experiments and limitations of applying such data in arm dynamics research must be considered.

A method for measuring kinesthetic RT was reported by Vince (1948). Subjects pulled a cord, attached to a pointer, in response to a visual stimulus. When the required force was increased from about 1.3 Kg to 3.2 Kg the RT increased from 0.19 seconds to 0.35 seconds. Vince concluded that the additional 0.16 seconds represented kinesthetic RT. Hick (1949) varied the force required and the response movements and established that the incremental RT depended on both /the added force and the intertia of the limb that the muscles were "set" to overcome./ Thus, a wrist twist response had greater "kinesthetic RT" than did an arm pull when the same incremental force was added to the lever. Hick concluded that the delay may be due at least in part to the elastic coupling of the mass of the arm to the control, and that the kinesthetic RT reported by Vince probably represented a combination of factors.

Chernikoff and Taylor (1952) mounted a sensitive accelerometer on a horizontally extended arm restrained by an electromagnet, then released the arm and measured the time until deceleration commenced. The RT to the sudden arm displacement measured in this manner was only about 0.12 seconds. However, when the arm release was used to signal a conventional key release response with the other arm, the RT was similar to the usual auditory or tactile RT. Johnson (1960) measured the reflex response time of posture-setting muscles and determined that it was so small (about 0.02 seconds) as to be negligible in a "first-order-of-approximation model" of the posture-setting mechanism. Hathaway (1935) studied the action potentials of muscles when subjects extended the elbow in response to a signal. Initially both agonist and antagonist were slightly active, then the antagonist activity tapered off as the agonist activity came in strong. A 0.06-second time delay was measured between the first electrical acitivity and the start of movement.

The action potentials from a number of separate muscles during various movements was studied by Sperry (1939). He concluded that the large postural muscles of the upper arm and shoulder could contract just as rapidly as the muscles of the lower arm, and that the comparative slowness of gross movements appeared to be due to inertia. The maximum rate of fine movements did not appear to be limited by the load but by the intrinsic time delays of reflex circuits. Diamantides and Cacioppo (1957) constructed a model for the voluntary (biomotor) system using reaction time of 0.2 sec., a (typical) second-order system to represent the muscle dynamics, and a first-order lag to represent the dynamics of continuous feedback. Their model indicated that the contribution of the neuromuscular dynamics was less significant than reaction-time in shaping the output response curve. Without continuous proprioceptive feedback the system would tend to be unstable unless greatly reduced, thereby increasing the relative importance of the inertial factors. On the other hand, Partridge (1961) in a simulation of muscle control reflexes reported that, "the simulation makes it clear that muscle "lag" effects reflex time more than central delay." From these observations it may be concluded that as the load on a limb is increased and the movements become more reflex in nature, the significance of strength and inertial characteristics in determining performance will increase.

McRuer and Krendel (1957) performed a cross-correlation between strobe light stimulation and electroencephalographic (EEG) response. A delay of 0.035 - 0.07 seconds was observed between the fundamental frequency of the stimulus and the evoked response. It was concluded that this delay represented the latencies of the afferent visual process. Efferent conduction and synaptic delays between higher centers and the upper extremity musculature were estimated to amount to 0.01 - 0.02 seconds, and muscle contraction time was estimated to require 0.02 - 0.04 seconds. Consequently, the theoretical lower limit for visual-motor RT was established at 0.07 - 0.13 seconds. McRuer and Krendel's review of Elkind's (1956) tracking data reported time delays ranging from 0.10 to more than one second, established by the "best-fit" describing function. The time delay term became smaller as the task became more continuous. In general, the reaction time delay for tracking a particular input is approximately; a) from 0.25 to 0.3 seconds for widely-spaced discrete steps, b) 0.20 seconds for closely-spaced random discrete steps, and c) 0.15 ± 0.03 seconds (for random appearing forcing functions). Russell (1951) noted that the RT term for his tracking experiments was reduced from 0.48 seconds to 0.28 seconds as more high-frequency power was added to the input spectrum. Diamantides (1956) used a 0.25 seconds delay to represent RT in model of the human pilot, but reduced this value to 0.2 seconds in a latter study (Diamantides and Cacioppo, 1957). Henderson (1959) observed that the RT term in his tracking data fell from 0.17 to 0.15 seconds as the gain of the compensatory display was doubled.

The reaction times measured in discrete stimulus-response experiments have not been related to the reaction time factors derived from continuous tracking tasks, although both measures are of the same order-of-magnitude. The relationship of individual differences in one type with those in the other type should be investigated.

The inertia, stiffness, and damping of the human upper extremity comprise the "output impedance", a complex variable quantity. Some output impedance is under voluntary control: stiffness is dependent on muscular tension and postural attitude; active damping can be adjusted over a wide range. However, fixed properties of the limb limit the range of responses which may be adopted, and the interactions of muscular tension with accuracy and speed of motor tasks suggest that optimal characteristics may exist for every task.

Krendel (1958, 1960) noted that manipulation of the input impedance of a control, crank, pedal, or lever can markedly alter the maximum rate of power transfer. Krendel suggests that these effects are analagous to impedance matching in electrical circuits with maximum power transfer occurring when, the reactance of the control is equal but of opposite sign to that of the limb, frictional resistance of the control is minimal and the useful load equals the sum of the internal resistive and external frictional losses. Since numerous studies have demonstrated that certain classes of human control performance are optimum at specific values of required force and amplitude, an impedance matching concept may be useful for even submaximal efforts. The manipulation of the input impedance as a function of task variables and individual differences in limb output impedance, to insure optimum performance, is a desirable goal which deserves detailed investigation.

A number of measurements of the moment of inertia of the human upper extremity and upper extremity segments have been reported. Most of these measurements were obtained from dissected human cadavers, although some were obtained from living human subjects. The cadaver data are accurate for the particular body of body segment used, but the limited availability of cadavers would have made a representative population difficult or impossible to obtain; the cadavers studied were generally older, shorter, and of lighter weight than the typical working man of today. Measurements of physical characteristics of limbs of living subjects can be obtained by the "pendulum oscillation" method, the "quick release" method, construction of "volume contour maps", or by calculations using volume data and x-ray photographs. A critical review of the literature dealing with measurements of moments of inertia of the human body and body segments appears elsewhere (Duggar, 1962).

Moment of inertia, one of the components of the output impedance of the human upper extremity, can be estimated or measured by several alternative methods. By comparison with measurements from dissected cadavers it whould be possible to estimate moment of inertia to within 20-30 percent. It is doubtful if other components of the ouput impedance can be specified more precisely.

The time characteristics of muscular tension during isometric contraction were investigated by Wilkie (1950). The time required for the tension to reach its final value was related to shortening of the active elements as the passive elastic elements lengthened. By measuring the force-velocity characteristics in isotonic contractions, sufficient data were obtained to determine quantitatively the compliance of the limb. Compliance was found to decrease with increasing tension. At two-thirds maximum flexion force about the elbow, the equivalent compliance at the hand was computed to range from 0.6 to 3.6 cm/megadyne for the five subjects tested. Johnson (1960) measured the compliance of the hand with respect to dorsal and palmar flexion about the wrist and reported values similar to those recorded for the forearm by Wilkie. With the hand held rigid the measured compliances were about 2 cm/megadyne, increasing to about 10 cm/megadyne in the normally held hand. Compliance of about 3 cm/megadyne when holding the hand normally was observed in a subject with Parkinson's disease, while a spastic patient's compliance was 50 cm/megadyne.

It has been well established that the velocity of shortening of a muscle restricts the amount of tension which can be developed. Consequently, the available force for work decreases as the rate of contraction increases. Fenn (1938) concluded that the true force-velocity relation is exponential, viscous friction making only a very small contribution. Hubbard and Stetson (1938) agreed that internal resistance has practically no significance. Although a large passive internal impedance may be used to provide a source of damping with electrical circuits, biological systems cannot use this method unless it can be by-passed during voluntary movements. It appears, then, that the force-velocity relation is limited primarily by the maximum rate of a chemical reaction and modified only slightly by a true, passive internal damping.

Johnson (1960) indicated the for relatively slow movements requiring at least moderate muscular, force, all damping due to joint friction and viscous friction of the muscles is negligible compared to that accomplished by sensing error. The significance of passive internal damping during movements requiring minimal force and various rates of contraction has not been investigated. Taylor (1957) concluded that damping in limb movements may be carried out automatically in spinal feedback loops. Fitts (1951) observed that skilled subjects generally exhibit critically damped responses. However, if the arm is carrying a heavy load, or if the gain is too high, the movement termination may be characterized as underdamped. Fitts therefore predicted that "there is an optimum gain or stiffness for any response and that efforts to produce higher rates may lead to unfavorable muscular tenseness and loss of fine control."

Other investigators, (e.g., Davis, 1956), have reported unusually high levels of muscular activity when precise tasks are clumsily performed. /When task characteristics are changed, the operator's optimum muscular gain may also change./ Henderson (1959) reported that in a tracking task the human operator reduced his gain when the display gain was increased, but the limb-lever system natural frequency was also reduced and relative damping increased. It is hypothesized that the reduced tension associated with the lower gain increased the compliance of the limb, thereby reducing the natural frequency. If the damping coefficient were constant, the increased compliance could account for the increase in relative damping. Such an analysis has implications consistent with Fitts' (1951) prediction of optimal gain, and of underdamped oscillations occurring if gain is too high.

Smith (1961) observed that the gross response of the forearm to step commands depends on the dynamics of the load to which it is coupled. However, the muscular forces developed were relatively constant for each individual regardless of the load dynamics or magnitude of command. Smith compared the response to that of a perfect relay, or "bang-bang" servo, with error a nonlinear function of the stored energy in the load. A possible internal computation for control of a system with these properties is to exert muscular force proportional to the sign of the error minus the stored energy. It was observed that the muscular force applied against a high frictional load during a step response is approximately unidirectional and the movement without overshoot. Asmussen (1952) demonstrated that "negative work" (work done by the load in stretching a muscle) has an energy efficiency which varies inversely with the speed of movement. Consequently, for fast movements a damping force can be actively generated with only minimal energy cost. This suggests that internal viscous friction is neither necessary nor desirable for damping of limb movements, since large decelerative tensions can be generated rapidly and efficiently by active muscular action. Unfortunately, there are no systematic data which define the range of characteristics of active muscular damping.

The inertial, elastic, and force-velocity characteristics of the limbs are important factors in designing systems for maximum power, or for most efficient man-generated power. Krendel (1958, 1960) reviewed the literature on man-generated power and concluded that the concepts of impedance-matching can be applied. Optimal power transfer conditions are:

$$R_{UL} = \sqrt{(R_M + R_{FR})^2 + (X_M + X_L)^2}$$

R_{UL} = useful resistive load.
R_M = man's internal resistance.
R_{FR} = wasted frictional resistance of the load.
X_M = mechanical reactance of the man.
X_L = mechanical reactance of the load.

Additional improvements in power transfer can be obtained by minimizing R_{FR} and adjusting $X_L = -X_M$. Krendel stated that X_M is less dependent on conditions of exertion and time than is R_M. However, evaluation of both terms for practical applications will require extensive additional research.

Wilkie (1950), surveying the literature on human power, reports that the coupling of the limb to a matched load is the limiting factor for achieving maximum power transfer for single movements lasting brief periods. Maximum efficiency of power transfer for prolonged periods is obtained when the applied force is about 50% of maximum and speed of movement about 25% of maximum. Considerably greater power can be transferred at greater speeds of movement against less force, but only at the sacrifice of chemical efficiency. Garry and

Wishart (1931), for example, observed maximum metabolic efficiency per unit of work output during bicycle pedaling at 52 rpm, while all energy was absorbed in the "no-load" movements at 125 rpm. A fundamental difference between trained and untrained cyclists was observed in the no-load energy costs. There is no evidence to indicate that such considerations cannot be applied to the analysis of work performed by the upper extremities.

Koepke and Whitson (1940) studied unilateral single movements of the right arm. Weights ranging from 6 to 21 lbs were accelerated across a table top in various directions and distances while velocity, acceleration, and work rate were recorded periodically. In general, the size of the weight had little effect on the power developed but did change its rate of development. Time to reach maximum power was 0.11 seconds for the 6 lb, and 0.17 seconds for the 21 lb weight. Average maximum velocities were 180 in/sec and 110 in/sec for the 6 and 21 lbs respectively. Koepke and Whitson noted large individual differences among their 6 subjects, although all were young males in good condition.

Investigations of time patterns of movement have been numerous, but have not included physical descriptions of the subjects. Peters and Wenborne (1936) studied the time pattern for moving a stylus over a segmented track and found identical patterns when moving toward or away from the body. Starting and stopping time were the same regardless of the length of the path. "Resolve" to move at either maximum or normal speed changed peak velocity, the acceleration and deceleration patterns. Taylor and Birmingham (1948) reported that maximum rate during 5.75 to 9 cm movements of a nearly frictionless joystick during tracking of step functions ranged from 93 to 209 cm/sec. /Glanville and Kreezer (1937) suspended the arm of their subjects from the ceiling so as to avoid the effects of gravity while measuring velocity of horizontal movement. Forearm flexion and extension average velocities for those portions of the movement when the forearm was flexed between 15° and 90° are listed in Table 7./ Wilkie (1950) measured peak velocity of forearm flexion without correcting for gravity, but the reported peak values (6-7.8 meters/sec) were approximately twice the average velocities observed by Granville and Kreezer. The inertia of the arm apparently caused the acceleration to continue well past the first 15° of movement during maximal flexion or extension. Changes in either the friction or inertia of an action may be expected to affect velocity or acceleration time, as has been reported by Orlansky (1949). Sperry (1939) studied electrical properties of moving muscles and concluded that the comparative slowness of overt movements driven by large muscles seems to be due to factors of inertia rather than physiological differences. By flexing the elbow to reduce inertia, Sperry was able to increase the maximum rate of reciprocal muscle movements of the entire arm by more than 50%. However, when a weight was added to increase the inertia to its original value the maximum rate also returned to its original value. Accuracy (Fitts, 1954) and preceding and succeeding manipulations (Wehrkamp and Smith, 1952) have also been shown to affect velocity of movement. When a movement is part of a complex task pattern, the maximum velocity is dependent on a number of factors, some of which are poorly understood.

3. Operational Considerations

Although the physical characteristics of the upper extremity directly limit its dynamics, other less defined properties of the limb and central control loops also effect both the dynamic and static characteristics. Craik and Vince (1943) outlined the factors they felt affect accuracy of a movement: a) the limb used, b) the mean position of the limb and points of support, c) the amount of movement, d) the force necessary to make, and e) its direction. Variables such as fatigue, distractions, total task framework, and training are also relevant.

The term "range effect" has been applied to the tendency of the human operator to overestimate short distances or small pressures and to underestimate large values. The range effect has been observed in both static and dynamic tasks, although the actual definition of "short" or "small" and "long" or "large" vary from task to task and with the subjects' training. In a positioning task with delayed visual feedback, Weiss (1955) has shown that the range effect also depends on the order of presentation of stimuli and is a greater proportion of total estimate at the shorter displacements (maximum displacement used was only 2 inches in this study, but an earlier report by Weiss, 1954, used displacements of up to 10 inches with similar results). Fitts (1954) observed that in a reciprocal tapping test with a 1 oz. stylus, over- and undershoot errors were equally frequent, but with a 1 lb stylus, undershooting errors were about twice as frequent. Hick (1945) studied the precision of incremental muscular forces as responses to known discrete stimuli. Using an isometric hand control in a tracking task the subjects had to insert a step increase or decrease in force when the target gave a sudden jump. Changes in the steady force tended toward overshooting, particularly for the decreases. These effects were resistant to practice and were independent of the basic force (less than five pounds).

In an experiment conducted by Nadler and Goldman (1958), maximum acceleration and deceleration during a simple movement correlated highly with performance accuracy. Taylor and Birmingham (1948) studied the acceleration patterns in quick corrective movements for tracking step functions and also found acceleration to be a dominant factor performance. A nearly frictionless joystick was manipulated laterally from 2.25 to 9 inches in response to step functions in a compensatory display. Maximum acceleration and peak velocity increased with amplitude of response, but peak velocity increased at a slower rate. Consequently, movement time increased only slightly as amplitude increased. In both of the preceding studies, the subjects were given continuous visual feedback to monitor their performance. For visually monitored movements conducted at maximal rates, the principal variable adjusted by the human operator and the principal factor affecting relative performance appears to be maximum applied force. When visual monitoring is prevented and speed unimportant, force may no longer be the controlling variable. Weiss (1954) prevented visual feedback of results and required subjects to manipulate a fore-aft joystick in an attempt to reproduce pure position movements of one to ten inches. Weiss found that percent constant error and relative variability decreased as the movement range increased, although these differences were found primarily at small displacements. Pressure on the control was varied from zero to 30 lbs without effect. Weiss (1955) repeated his experiment using displacements of 0. 5 to 2 inches and again found that force had no significant effect. For static judgments of position, force appears to have little effect.

The discrimination thresholds of differences pressures (DL) have been shown to be similar for wheel, stick and pedal controls above 5 lbs. (Jenkins, 1947) The DL is between 20 and 25% of the standard pressure at one pound, but falls rapidly to 6-9% as pressure is increased to ten pounds. Between ten and forty pounds the DL remains a fairly constant proportion of the standard pressure. These results have been interpreted as support for spring loaded aircraft controls.

Failure to recognize the limitations of Weiss' positioning experiments, has caused confusion in interpreting the usefulness of pressure loading on controls. When performing dynamic movements, pressure has a pronounced effect. Bahrick, Bennett and Fitts (1955) required blindfolded subjects to rapidly deflect an elbow lever through a given angle and return it to its original position. Relative error decreased with increasing amplitude. However, it also decreased significantly at the smaller amplitudes with increasing relative pressure. When corrective movements were allowed at the extremes of each movement, the accuracy effect of pressure proportional to displacement was reduced, although moderate constant torque requirement remained beneficial. In general, the spring constant of the control increased the accuracy of position discrimination without visual feedback. Bahrick, Bennett, and Fitts suggest that the elastic constants, mass, and damping of the control interact with the physical constants of the limb to give changing effects on forces during movement. However, repeated attempts to explain the relationship between control dynamics and tracking performance solely on the basis of sensory factors have been unsuccessful. Bahrick, Fitts, and Schneider (1955) tested the hypothesis that accuracy of movement velocity is directly related to the damping and mass of a control. Their experiment involved performing circular and triangular motions with a joystick at a prescribed pace. Accuracy of movements were not significantly affected by spring loading although uniformity of velocity decreased as loading increased. As predicted, both damping and inertia improved uniformity of velocity. The relationship between performance of learned patterns of movement and continuous tracking movements is, however, unknown.

After an extensive review of the literature, Bahrick (1957) concluded that the forces used by an operator in moving a control are only indirectly related to the proprioceptive stimulus he receives during the execution of the movement, "and that studies to date have only scratched the surface of determining the underlying relationships." A later review (Bilodeau and Bilodeau, 1961) reported that, "there are excellent reports of the physical properties of control sticks (such as spring stiffness, damping, and mass) and of various spatial and temporal responses to these (accuracy, rate, and acceleration)." It should be noted that these references did not deal with the tracking of continuous, random appearing inputs, and that the most recent reference cited concluded that there has been very little progress in understanding these relationships.

Gibbs (1953) reported that although an isometric control produces tracking performance superior to that obtained with an isotonic control, this superiority is only manifest at points where the target decelerated. This finding is consistent with observations reported by Smith (1961) which indicated that error is a nonlinear function of the stored energy in the load.

According to Corrigan and Brogden (1948, 1949), constant velocity pursuit movements were most accurate when the movement was flexion or extension of the forearm-shoulder, and least accurate for adduction-abduction movements. Grant and Kaestner (1955) found that subjects seemed to prefer to track targets requiring movements directed medially from their dominant side. This preference for thrusting or extending rather than pulling or flexing motions became more important, in terms of error scores, as the subjects' tracking experience increased.

Fitts (1954) has examined the applicability of the concepts of 1) channel capacity, 2) amount of information contained in a movement, 3) noise, and 4) rate of information transmission to the human motor system. Fitts' subjects performed rapid tapping motions, alternating between two targets of varying size placed at varying distances from one another. The tapping responses were highly overlearned in order to assume that accuracy and variability of performance were limited primarily by motor system characteristics. Although Fitts recognized that the visual and proprioceptive feedback loops might also limit performance, these factors were not considered separately. Fitts specified the information capacity of the motor system, "by its ability to produce consistently one class of movement from among several alternative movement classes." Information was thus related to the force, direction and amplitude of movement. The statistical variability of these factors in reproducing a given response indicated limitations of their information content by internal noise. Fitts reasoned that if the channel capacity of the motor system is independent of the average amplitude and accuracy, it would be possible to show the interrelationship between amplitude, duration and variability of movement. Although industrial engineers have pioneered in showing that amplitude, time and precision are related in performance, the literature on motor skills has been replete with apparent contradiction due largely to a failure to recognize the independence of channel capacity.

When performance is specified in information terms and the operator works at his maximum rate, the information transmission per unit time should be constant for a wide range of amplitudes and required accuracies. Fitts devised such an index of performance (I_p) for his tapping task:

$$I_p = \frac{1}{t} \log_2 \frac{W}{2A}$$

I = binary index of performance in bits/second
W = width of target (tolerance) in inches
A = amplitude of movement
t = average time in seconds.

Not only did I_p remain constant for the reciprocal tapping experiment, but also for classical disk transfer and pin transfer tasks. Very large or very small amplitudes gave poorer performance due to the inherent noise, physiological limitations of the limbs, and visual restrictions.

The results of Fitts' study are particularly pertinent to the question of linearity in human motor performance. For a system to be truly linear, the superposition theorem must hold and movement duration should be constant for any amplitude. Within limits this can be accomplished when men work at their maximum pace (in terms of information transmission), but unless relative precision remains constant, amplitude and movement time will be directly related. However, when the human operates at a figure less than his channel capacity it is possible for him to independently vary amplitude, rate, or accuracy. These features of human adaptability within a fairly large but finite channel capacity have caused such writers as Elkind (1953) and Stark (1961) to report linear tracking by the human operator, while others such as Adams (1961), Birmingham and Taylor (1954), and Mayne (1950) report that human tracking behavior is basically nonlinear. Under certain conditions human tracking performance may be closely described by linear equations, but it is easy to demonstrate the nonlinear aspects of human performance by simply comparing performance on an easy task with that on a difficult one. The effects of task and procedural variables in deviations from linearity remain, for the most part, undefined.

Although Fitts' experiments give hope of eventually developing a unifying concept of motor capacity, there are reports which cannot be readily interpreted in terms of information transmission. Peters and Wenborne (1936) studied the time pattern of maximal voluntary movements in the guiding of a stylus down a straight track and a spiral track. Average speed over the spiral path was about one-half that measured over the straight path, but this reduction in velocity did not apply to all segments along the path. The authors concluded that control of the spiral movement was intermittent and therefore only possible at a reduced rate of speed. If continuous movements are segmented in terms of information transmission, the applicability of this type analysis to complex tasks may not be practical.

Davis, Wehrkamp, and Smith (1951) and Wehrkamp and Smith (1952) used a Universal Motion Analyzer to study the interaction of movements and manipulations. Their experiments involved successive reaching for a knob or lever, grasping, and then either turning or pulling the device as required. It was determined that, "the pattern of a manipulation defines not only the time of muscular response in the manipulation, but also the time of muscular response in travel between successive motions." In addition, increasing travel distance increased manipulation time. Manipulation time was reported to be considerably more improved by practice than was travel time. Simon and Smader (1955) confirmed the importance of these interactions in the placing of washers on pins. When the task was made more difficult by requiring a visual discrimination of the upper side of the washers all time components, including "travel unloaded," increased. It is difficult to explain increased unloaded travel time from the pin to the washer bin and its affect on manipulation time.

Another important operational characteristic of the human upper extremity is the tendency to develop muscular fatigue after prolonged exertion. Little research has been reported on the problems of muscular fatigue in continued operation of alternative control designs, a deficiency largely the result of its insignificance in many tasks compared to visual fatigue, boredom, reduction of motivation after prolonged performance, etc. However, muscular fatigue may be an important consideration, particularly for persons with impaired muscular capabilities. The Godwin and Wallis (1954) review of literature emphasized the lack of data concerning muscular fatigue and alternative crank and handwheel specifications.

Tracking studies in which cranks or handwheels were employed have generally reported that optimum tracking occurred when winding speeds were high. However, test periods were short and no attempts were made to predict the effects of muscular fatigue due to prolonged performance. For example, Helson (1949) reported that visual fatigue was more important than muscular fatigue after 15 minutes of tracking using high speed cranking. Since high speed cranking produced the least error in Helson's tracking studies, it was recommended that crank control systems require turning rates of 150-200 rpm. Godwin has questioned whether such high rates may not prove disadvantageous where the control is in continuous use. A Goodyear Aircraft Corporation study (1955) reported that in piloting an aircraft simulator with an excessively insensitive control, "the pilot exhibited fatigue and decreased efficiency" after ten minutes. With a more sensitive control these effects were not noted.

Muscular fatigue due to high rates of work output over prolonged periods of time have been extensively studied for specific tasks, such as climbing steps, pedaling a bicycle ergometer, etc. Large individual differences in resistance to fatigue have been observed for these tasks. Studies of industrial workers have indicated that work methods are often an important factor in fatigue of unskilled and semiskilled laborers. In fact, the basis of time and motion studies is that work methods are dominant factors in determining individual differences in skill, output rate, and muscular fatigue. Continuous control tasks requiring moderate to large rates of power transfer, particularly if used by heterogeneous groups of operators covering a large range of size, age, and constitution, should therefore be designed with consideration given to possible methods of operation. Clark (1954) suggested that the operator be allowed to adjust his position slightly from time to time, using different muscle combinations for the same task. Gilbreth's principles of motion economy can, to a limited extent, be applied to the design and operation of continuous control systems. Distance of movement should be kept small, operators should be taught to make smooth, cursive movements without suddent stops, and extremes of velocities in movement should be avoided.

Although effort of operation can be reduced by use of power assist devices and high control ratios, excessively sensitive controls may increase fatigue due to prolonged operation. Coleman (1962) stated that the controls of a new aircraft had purposely been made stiff, "to improve long-range flight weariness ordinarily brought on by jets with 'touchy' controls." Muscular tension caused by unstable or excessively sensitive controls may be a serious handicap, and there is some evidence that muscular tension due to emotional involvement, imminent danger, etc., may impair performance and produce fatigue in the same manner (Davis, 1948).

B. The Evaluation of Individual Capabilities Related to Steering

The evaluation of individual capabilities and limitations related to performance in steering or tracking has received little direct attention. Although numerous tests have been used to select candidates for pilot training, skilled and semiskilled industrial employment, vehicle drivers' licenses, etc., the arbitrary determination criteria and the uncontrolled effects of prior training and motivativation prevent generalization about control abilities. To facilitate the design of control systems, vehicle operator selection methods, and to assist in the rehabilitation of disabled persons, knowledge in the following areas is needed:

1) The range of control performance measures likely to be encountered in both trained and untrained population groups.
2) The effects of age, constitutional characteristics, and specific disabilities on control performance.

3) The range of task difficulties for which individual differences in capability will be small, and the interaction of particular forms of task difficulty with physiological limitations.

4) The biomechanical factors of greatest importance to control behavior.

A number of studies, not directly involving steering type tasks, have provided information relevant to these questions and are included in this review. However, any interpretations of results of static, positioning, or reaction time tests as applied to steering capabilities must be regarded as preliminary until verified experimentally. The relationship of steering to gross muscular strength, physical fitness as measured by the Harvard Step Test, bicycle ergometer performance, and other tests for which large individual differences have been reported, is unknown.

Several investigators have reported significant individual differences in tracking performances. Poulton (1957a) noted that individual differences in response patterns during pursuit tracking are fairly constant, but may be altered by special training. Krendel (1952) demonstrated that the spectral density of the output and error in compensatory tracking may vary greatly between individuals. Siddall and Anderson (1955) used constant-speed handwheel-cranking with a compensatory display to demonstrate that individual variations in fatigue effect are large. All of the 21 subjects (18-33 years of age) used by Siddall and Anderson were able to give 10 minutes of error free performance during training sessions. However, significant individual variations in both number of errors and mean duration of errors in consecutive 1/2 hr. periods of a two-hour run were observed.

On the other hand, Elkind (1956) found only small deviations in tracking characteristics within and between 3 subjects during compensatory tracking of a moderately easy input course. However, Elkind's subjects did not use any control device (they manipulated a pencil-like device across the face of a cathode ray tube) and amplitude of motion was only ± 1 inch rms. Welford (1960) stated that for easy physical tasks individual variation is small since central processes dominate response characteristics. Welford concluded that after 12 years of progress in the measurement of sensory-motor performance, "the point which has emerged from a number of studies is that there is much greater uniformity between the reaction time of different individuals than between their time to make relatively unguided movements: in other words, the central mechanisms appear to function with less individual variation than do the peripheral." From the above considerations it may be concluded that individual variations in tracking will be more pronounced as a control system requires larger amounts of force and movement.

Seashore (1940 a) investigated motor skills involving small movements and close tolerances and reported that the principal variables affecting individual differences were speed, strength, and precision of movements. The size and stability of individual differences were not determined nor kinds of underlying or influencing factors. Seashore (1940b) also attempted to correlate performances on a number of classical motor skill tests (reaction time, key tap rate, etc.). He determined that qualitative similar patterns of action in two tests resulted in better correlation of results than did similarities in the anatomical units involved.

Seashore, Dudek and Holtzman (1949), finding little correlation among classical steadiness and precision arm-hand tests, concluded that static abilities are not important determinants of individual differences in refined motor skills. Summarizing determinants of motor skills, Seashore (1951, page 1353) listed three groups of factors basic to individual differences in any human ability:

1) the physical constants of the various organs (especially sense organs, nervous system, and musculatures) employed.

2) the general, qualitative pattern of action components involved.

3) the degree of refinement of these action components with respect to both strength and timing to produce an optimal pattern of action.

Unfortunately there has been no systematic study to clarify the relative importance of these factors to tracking ability.

A dimensional analysis of psychomotor skills was done by Fleishman (1954) "to provide a functional classification of abilities adequate to account for individual differences in psychomotor performance." A battery of 38 psychomotor tests were administered to several hundred airmen. Twelve factors were extracted from a correlation matrix of the results. Unfortunately the factors identified had only moderate loading for any of the tests and no data were reported regarding individual results as related to constitutional or anatomical factors. Fleishman (1958a) also studied static reactions, and positioning movements skills in a group of 200 airmen in a wide range of classical tests. Since many of the variables showed no significant correlation with any other variable, only three general factors were identified. It was concluded that static reactions are different from positioning movement in the tested sample. To complete the picture, Fleishman (1958b) gave 31 tests dealing with movement reactions to 204 airmen. Dominant factors identified were: a) response orientation, b) fine control sensitivity, c) reaction time, d) speed of arm movement, e) arm-hand steadiness, f) multiple limb coordination, and g) rate control. None of Fleishman's tests required much exertion or involved more than six inches of motion. Adams (1961), reviewing tracking behavior, concluded that the results of research on variables influencing individual differences in motor behavior indicate inherent complexity in motor task performance.

Individual differences in speed of operation of self-paced tasks have been reported in the literature. For example, Huffman and Gottlieb (1954) studied performance on three, everyday tasks (operating a telephone, ladling soup, and use of a hanger). For both maximum and "natural" pace of performance, he found that interindividual variations in rate were much larger than intraindividual differences in day to day performance. Wuest (1951) compared maximum frequencies of rhythmical to-and-fro movements of upper extremity segments with the "natural" or "personal tempo" frequencies among 15 subjects. Maximum frequencies averaged about 50 percent faster than the natural frequencies. Differences from one side of the body to the other were small in comparison to interindividual differences; however, both maximum and natural frequencies were slightly faster on the dominant side. Natural frequencies of upper arm movements were reported to vary over a range of five to one, more than three times as great as those for finger movements.

Individual differences in constitution and anthropometric measures have been described by numerous investigators. Damon and McFarland (1955) reviewed the literature on occupational anthropology and concluded that: a) the physique of workers in certain occupations differ consistently from workers in certain other occupations, b) certain physiological processes such as aging and maturation may differ from one occupational group to another, and c) certain occupational groups can be differentiated by anthropometric measures, but generalized constitutional descriptions differentiate the same groups more clearly. Damon and McFarland also compared anthropometric data from a group of "champion" truck drivers to regular bus and truckmen measures. The champions were younger, taller, stronger (right hand grip strength), more mesomorphic, had longer forearms, necks, and faces, and had broader shoulders and greater sitting heights.

A method for classifying human physique which has been used with some success in occupational anthropology is Sheldon's somatotype (see Sheldon, Stevens, and Tucker, 1940). The somatotype consists of rating each of five body areas on a scale from one to seven and of classifying the overall anatomy in its endomorphy, mesomorphy, and ectomorphy. Although the somatotype has successfully differentiated certain occupational groups on a statistical basis, its relationship to motor skills has not been clearly established. Sills (1950) performed a factor analysis of somatotypes and performance on a battery of 16 motor skill tests. In general, tests stressing motor ability had positive loadings on mesomorphy and negative loadings on endomorphy. However, strength and speed factors had no significant loading in respect to somatotype components. Janoff, Beck, and Child (1950) studied the relationship of somatotype to several physical characteristics including visual and auditory reaction time. In reaction times, only the auditory correlated significantly with any component ($r = 0.33$ with mesomorphy). It is probably valid to infer certain general physical limitations or capabilities for persons having extreme somatotypes; but for the majority of individuals with less extreme constitutions the significance of physical factors relative to other factors (e. g., psychological and environmental factors) remains undetermined.

Pike and Butterfield (1949) evaluated the physical requirements for drivers of heavy trucks. Leg length was critical in gear shifting ability (the minimum length depending on the particular vehicle dimensions) and arm strength in turning the steering wheel at low speeds. All other requirements were reported to be dominated by these two criteria. As a result, standards of 100 ft. lb. impulse and 75 ft. lb. continuous (15 seconds) force were for drivers of the Diamond T tank transporter. A sample of 55 male and 5 female subjects were tested on these force requirements and only 28 men could meet the suggested standards. A large range of maximum force was observed for this test group, right turn forces averaged slightly more, than left turn forces although both arms were used. Of a group of 77 military recruits only 12 were both tall and strong enough, 5 of the 77 recruits were strong enough but not tall enough, and 37 were sufficiently tall but not strong. Following several months of training 23 of the latter 37 men were retested and only two failed to meet the suggested standards for strength.

McFarland (1946) has discussed the force requirements of aircraft controls and noted that since different pilots possess a range of strengths, design criteria should be based on the weakest pilot having sufficient strength to maneuver in critical events, such as loss of an engine during takeoff. However, regarding desirable force for "feel" effects pilots preferred larger values. McFarland reported that in the development of the L-49, elevator force of 35 lbs, was rejected as not giving proper "feel", and 50 - 80 lbs. was recommended as the desirable force. Aircraft pilots are generally acknowledged to be healthier and more muscular than average as a result of the selection process involved in their acquiring and maintaining such employment. In industry and private life, however, there may be many individuals who are unable to exert large forces. Darcus (1954) noted this fact and concluded that, "it is questionable whether anatomical and physiological capabilities and limitations of the operators are receiving adequate consideration." In an extensive review of the literature on human factors in control design, Godwin and Wallis (1954) emphasized the fact that, "the more complex control systems will involve questions of selecting the most suitable personnel, and so designers should know something of the spread of ability among potential operators."

One source of individual differences is the manner in which the operator consistently trades speed against accuracy. Fitts (1954) has shown that these two factors are not independent. However, Fitts did not provide information regarding individual differences. To what extent training and physiological or anatomical factors determine individual differences is unknown.

The dimensions of the operators workspace may also influence individual differences. Unless dimensions are adjustable to the individual operator, the control device-limb arrangement will vary with body dimensions of different operators. Ross (1957) demonstrated that upper extremity force available for manipulation of a control varies by large and predictable amounts, depending on the angular relations of the limb segments. Vince (1948) and Hick (1949) observed that when the arm-control arrangement was such as to minimize the effects of arm-inertia during control operation, increased resistance in the control increased reaction time. On the other hand, when manipulation of the control involved overcoming considerable limb inertia, the effects of added control resistance were small or nonexistent. Hick speculated that these differences were due to the elastic coupling of the mass of the arm to the control handle, and to differences in the "set to respond" for the two movements. Individual differences in limb force/inertia ratio should also effect reaction time. The relationship of workspace dimensions, and of the control gripping arrangement, to continuous tracking performance remains to be verified.

Entwisle (1960) reported that age affects reaction time but not movement time in a tracking task. This difference became more apparent as the response complexity increased in laboratory tracking experiments. Entwisle was also able to show changes in the acceleration pattern of movements as a function of age. Griew (1958) noted that age affected amplitude of tracking movements but not phase lag.

Individual differences in tracking extend to average performance and to variability of performance. The Goodyear Studies (1955) found that variance in performance was a more satisfactory index of change in control parameters than was an average error criterion. The physiological factors underlying individual differences in performance variance remain undetermined.

One possible source of individual variation not related to gross physical strength or anatomical factors involves the interactions of simultaneous responses, tensions and cognitive aspects of task performance. Freeman (1938) noted that a tension producing load may facilitate one type of activity and impair another. In a laboratory experiment, non-habituated tasks were found to be facilitated, or not inhibited, by greater tension loads then were habituated acts. Adults were less affected by greater tension than were children. Meyer (1953) summarized the literature on interaction of simultaneous responses and concluded that tracking variability should increase with the degree of induced tension.

Adams (1954) studied the hypothesis that induced tension affects the magnitude or latency of response but not the habit associated with it. A light-matching test was used in which the subjects manipulated two spring-centered handles to match stimuli in rows of lights with the proper response lights. Tension was induced by requiring subjects to depress a counterweighted foot stirrup. Adams was unable to verify the original hypothesis. Campbell (1936) determined that cognitive aspects of performance have large effects. Greater practice and greater cognitive involvement increase the correlation in performance between tasks. Large changes in cognitive involvement changed performance of actions . Individual differences in cognitive involvement and induced tensions may affect tracking performance and distort experimental results if uncontrolled.

C. The Servo Element Analogy as a Research Tool

Over the past 20 years literature has accumulated in which the feedback theory of closed-loop servomechanisms has been adopted as one model of man-machine tracking systems. Although this approach has restrictions, it provides a useful and descriptive frame of reference and will be developed below. The similarities between the manner in which servomechanisms and men function in control systems is striking. However, if environmental, task, or procedural variables are altered, significant differences may be apparent.

Man performs as a nonlinear, adaptive, component of a system, and a transfer function for the human operator is valid only for the specific conditions for which it was derived. Birmingham and Taylor (1954) cautioned: "the human transfer function is a scientific will-o-the-wisp which can lure the control system designer into a fruitless and interminable quest." Over limited ranges, as yet unspecified, human performance may be conceptualized as linear, but nonlinear adjustability is a fundamental asset of the human operator. From this dynamic quality, man can utilize a variety of control systems and maximize the accuracy of his performance in many ways. Adams (1961) stated "nonlinearities are an inherent, and indeed the most interesting and challenging, aspects of the human operator." The servo-system approach is the most logical frame of reference within which to study nonlinearity and linearity in performance, since it is a model which quantitatively and qualitatively defines these phenomena.

Specific mathematical expression derived by the many investigators in this field are not included in this review. In general, first order differential equations can be fitted to human performance data but the coefficients depend on a multitude of factors and a wide range of values have been empirically derived (see McRuer and Krendel, 1959). Moreover, the manner in which these coefficients change as a function of environmental, task, and procedural variables should be investigated for they may contain valuable behavioral and physiological insights.

Servomechanisms may be generally described as self-regulatory devices characterized by one or more feedback pathways. The elements included between the origin and terminus of a feedback path constitute a closed-loop system. In it, the system output is compared with the input signal, the resultant "error" actuating further output. In its simplest form this is an error-nulling system, the characteristics of which can be closely approximated by differential linear equations. Servo-theory is particularly useful in dealing with properties of response such as stability and oscillation that cannot be attributed to any one element of complex, multicomponent, systems. The "black box" approach reduces the need to speculate on the multitude of transformations which occur as a signal traverses the chain of components; and it eliminates the need to designate the components themselves. System response can be specified in time domain by comparing a weighting response to an impulse function. However, since continuous control systems are the major analytical interest, it is preferable to use the frequency domain transform of the weighting function, i. e., the transfer function. The transfer function of a simple servo system is a complex ratio reflecting lead-lag characteristics and gain as a function of frequency.

Tustin (1947) is generally credited with first reporting the similarity of human operator behavior in manual control systems to that of equalizing elements in servo systems. Tustin's insight was derived from observations of pursuit tracking performance simulating manually controlled, electrically operated, gun turrets on tanks. Unfortunately the targets used in his tracking experiments were of modest complexity, so that the nonlinearities introduced by the human prediction apparatus limited the appropriateness of the linear transfer function. He also noted a discontinuous or intermittent corrective output from the turret operators which he described as "jerky." The primary benefits of his study were not the mathematical equations he derived but the principles he first articulated. Briefly stated they are: a) Observed tracking behavior of random appearing inputs can be expressed as a mathematical formalization on a statistical basis. A linear function will closely approximate this behavior when the discontinuous action can be explained as random noise. b) The human adaptive behavior qualitatively adjusts its movement patterns within its range of capabilities so that the equations describing these actions minimize the mean square error of the mathematical description of the input function. c) From item b, the human may be said to respond predictably to the insertion of linear compensation in the tracking system. This response may take the form of derivative control or positive phase-shift together with the adjustment of his gain to a value consistent with a reasonable margin of stability. d) The inherent discontinuous nature of the human response observed in the gun turret tracking operation appears to be a form of information feedback process by which the system dynamics are measured so that optimum movement patterns can be adopted as described in b) and c) above.

A Nyquist diagram, according to Russell (1951), can be used to describe a linear servo. Such diagrams would be useful in comparing different human operators, under the same or different conditions or the same operators under different conditions. A Nyquist diagram of system response also may be used to determine types and amounts of linear compensation that could be added to improve system performance. Russell's subjects tracked random appearing inputs consisting of the sum of four non-harmonically related sinusoids selected to represent low, medium, or high input bandwidth. A broad range of system dynamics were utilized in conjunction with a small aircraft-type handwheel. The handwheel had moderate coulomb friction (exact amount was not reported) but no spring constraints. The results indicated that for these particular conditions the human operator's tracking performance could be approximated by a single-integration device with a time delay, some derivative control (lead term), and means to attenuate its output if it would improve performance.

Russell's Nyquist plots also indicated several features of the nonlinear adaptive behavior of the human operator. Specifically, it was noted that a shift in the frequency spectra of the input signal caused a shift in gain and phase, even for the input frequency components which were not altered. Both gain and phase for a given frequency tend to decrease as the frequency spectra changed to predominantly higher frequencies. Consequently the mathematical describing function of the human operator was different for the two conditions. Physiological factors were also found to influence the describing functions since, for example, a subject who suffered from a bad cold had very low gain and failed to compensate in his customary manner. Ingestion of alcohol reduced both gain and the ability to generate a lead term. Also, urging subjects to do better was followed by an increase in gain.

In an additional experiment, Russell (1951) was able to provide convincing evidence supporting Tustin's hypothesis that the high frequency, discontinuous noise inserted by the operator is a part of an information feedback system. Russell observed that when the system dynamics were suddently altered, depending on the type and degree of change introduced, the subject changed his internal dynamics within a few seconds. Thus, his overall operation remained relatively constant. However, when filters were placed in the control output circuit in order to eliminate the effects of this high frequency "noise" and to smooth the output of the operator, performance was reduced and compensations for changes in control dynamics were not so rapid.

The most extensive research study concerning the mathematical approximations of the human operator's tracking performance was performed by Elkind (1956). Because subjects were highly motivated and no control lever or wheel was used, this study is believed to represent the upper limits of human tracking performance. The tracker manipulated a pencil-like device ("pip trapper") over the face of a cathode-ray tube in response to movements on the display so that any constraints on movement were due entirely to the mechanical and neurological constants of the human limb system. An extensive range of input spectra were used and describing functions derived for all experiments. A tabular summary of Elkind's data was assembled by McRuer and Krendel (1957, 1959) and appeared in Sheridan's (1961) review. Among Elkind's findings were the following:

a) There was little nonlinear transfer behavior for varying amplitudes from 0.1 to 1.0 inches. Although the closed-loop relative response magnitudes for the larger amplitudes were generally larger, the differences were quite small and inconsistent.

b) Gain and phase lag of the human operator decreased with increasing input bandwidth.

c) The pure time-delay associated with reaction time became smaller as the tracking task became more continuous through the addition of higher frequency components to the input.

d) The mean frequency of the input spectrum and its predictability were inversely related to the open-loop gain term in the operator's describing function.

e) The optimizing criterion of the operator appeared to be one that tends to minimize rms error.

f) No resonant peaks or sign of purposeful injected noise were noted in the error spectra. The discontinuous high frequency steps noted by Tustin and Russell are not characteristic of tracking movements of the unconstrained limb operating as a simple controller. However, it should be noted that Elkind's subjects were well trained for the simple nature of their task.

g) Response became more erratic and variable as the forcing function bandwidth increased. Consequently the appropriateness of linear equations to describe human tracking decreases and remnant power increases for increasing bandwidth.

h) Variations due to training or to time were not significant. Three highly trained subjects tracked at intervals separated by as much as four days. Analysis of variance showed no significant differences ($p > .01$ level). Standard deviation of the closed-loop amplitude ratio was 3% of the mean value, and standard deviation in phase was about 3°.

i) Pursuit tracking was accomplished with much less closed loop phase lag than compensatory tracking. Closed-loop amplitude ratios increased sharply with increasing frequency of stimulus for pursuit tracking; only a minor increase was noted in the compensatory situation. However, the advantage of the pursuit display was reduced at very small input particularly for the low frequency components.

A series of tracking studies using the Franklin Institute Simulator have been described and analyzed by McRuer and Krendel (1957). These studies involved two-dimensional compensatory tracking using a spring-loaded aircraft control stick. However, only the data for aileron movements were analyzed. McRuer and Krendel concluded that, "in general the Franklin and Russell simple trackers and the Elkind pip-trapper experiments yielded results which were fairly similar and consistent." Although the describing functions for these three studies were similar, the remnant term for the Franklin study was considerably greater. The addition of the task of simultaneously controlling two-dimensional movements and the addition of spring constraints to the control level increased task difficulty so that time variations in the operator's performance, injected noise, or actual nonlinear operations on the forcing function became significant. Average linear correlation of the output with the "best fit" human operator transfer function was considerably less than in the other studies discussed above.

Hall (1957) used an aircraft-type handwheel control with spring constraints to study the human operator describing function. The input forcing function consisted of white noise filtered through a low-pass third order binomial filter with corner at 1 radian per second. Although a two-dimensional tracking task was used, only the longitudinal (pitch) movements were analyzed. Controlled element dynamics were simple zero order, simple lag, and pure first order with a range of values for controlled element gain. Hall's results are fairly similar to those of Russell for similar control dynamics. However, Hall varied the control sensitivity and dynamics over a range not previously investigated. McRuer and Krendel (1959) include tabular data of Hall's describing functions in such a form as to facilitate comparison to Tustin's, Russell's, Elkind's, and the Franklin Institute results.

Mayne (1950), at Goodyear Aircraft Corporation, concluded that "no unique expression, or transfer function, can represent the human operator, who is believed to constitute a different mechanism under different conditions." Instead, Mayne proposed to match the human operator's response by adjusting nonlinear analog computer elements.

An examination of the equivalent synthetic analog system components would yield insights into the fundamentals of human performance and suggest methods of compensating for poor performances. A later Goodyear report (1955) described the synthesis of such an analog network closely approximating performances of individual, skilled pilots. Synthesis was sufficiently satisfactory so that a considerable period (30 seconds or more) would often elapse before the operator detected that the computer was in control. When the control feel and dynamics were changed the pilots were able to compensate rapidly and effectively over a wide range of task requirements. It was suggested that the variance of the pilot efficiency (non-steady describing function) may be a sharper criterion of system quality than such measures as rms error or time-on-target. Cacioppo (1956) reported studies with the Goodyear Dynamic Simulator where flight experience and training were shown to affect gain, "dither", anticipation and use of derivative information from the input signal. The individual differences among pilots with varying experience were evident both in the coefficients of their describing functions and in the manner in which these changed with task variables.

The Goodyear analog contained several nonlinear elements which, if present, could account for the remnant observed in the studies using quasi-linear describing function.

a) rate threshold function in series with the operator's linear dynamics,

b) a "clamping" or limiting function in series with the linear dynamics,

c) an anticipation or "perfect relay" function in parallel with the linear dynamics.

However, these elements were subsequently studied (a, b) with insignificant effects. Consequently, the exact nature of the human nonlinearities remains controversial and several alternative explanations have been advanced (see McRuer and Krendel, 1957, and 1959).

McRuer and Krendel (1957, 1959) performed an extensive review of all prior studies with sufficient data for derivation of describing functions. These data were assembled and converted into the simplest "best fit" equivalent equations to facilitate comparison of results. This compilation is a valuable source of basic data suitable for control design. Unfortunately the number of subjects used in all of the included studies was small, the subjects were primarily young and experienced, and no data regarding their anthropometric characteristics, specific capabilities, or physical disabilities were reported. In addition, all the included studies employed fairly sensitive control devices requiring no more than modest force to follow the input spectra. Test runs were short so that fatigue effects would not be evident. Consequently these results must be regarded as approaching the maximum capabilities of superior tracking operators under the conditions of these measurements.

The purposes of the McRuer and Krendel studies were to provide quantitative answers to the following questions (McRuer and Krendel, 1959, page 3):

1. "How does (will) the operator perform in a given situation, that is, what specific quasi-linear transfer function and remnant, or analog computer set-up, are required to describe his conduct?"

2. "How well can the operator perform and how do we make him behave that way, that is, what is the 'desirable' operator characteristic and under what circumstances is it achieved?"

Answers to these questions should be in terms compatible with conventional control system descriptions. Although a unique mathematical expression describing all human operators' performance would greatly simplify the task of answering these questions, no such unique transfer characteristic exists. The operator's response depends upon a number of factors (McRuer and Krendel, 1959, page 2):

1. The dynamic characteristics of the controlled elements, ----.

2. The type of input or forcing function driving the system.

3. The individual reaction delays, thresholds, etc., of the human during the particular operation. (There are variations between individuals and within individuals which are functions of both physiological differences and task experience. Any set of transfer characteristics ultimately proposed would have to allow for a variation in paraemters of this type.)

4. The motivation, attention, previous training, and general psychological and physiological condition of the human at the time of the operation.

The tabular data presented by McRuer and Krendel do not include all possibilities implied by 1 and 2 above but do provide sufficient data for approximate extrapolations covering a wide range of task variables. The effects of factors 3 and 4, however, are not elucidated by these data since all studies were performed under near optimal conditions with a select group of subjects for which individual differences might not be readily apparent.

Henderson (1959) used a first order control handle, compensatory display, and "white noise" target course in an attempt to estimate the transfer function with a correlation method. Henderson noted that it took 6 to 8 hours of training before an untrained operator was able to reduce his error to a consistent, minimum level. After the training period, a linear transfer function similar to those derived by McRuer and Krendel was fitted to the data. One finding by Henderson was that as the display (controlled element) gain increased, the lead term (use of derivative information by the operator) also increased.

None of the preceding studies systematically examined the problem of time variation of transfer characteristics, although the possibility of such variation contributing to the remnant was recognized. Sheridan's (1959) investigation into these effects was a necessary, long overdue step. Sheridan has documented the theoretical and practical difficulties of measuring the time-varying dynamics, developed a convenient measurement technique and reported a group of laboratory experiments. Unfortunately, the increase in uncertainty accompanying increase in temporal resolution inherently limits measurements in the describing function, slow relative to target frequency components.

Sheridan's orthogonal multiplication technique for the measurement of time-varying dynamics allows a time resolution of 15 seconds with only 5 to 10% error when the input signal consists of five relatively prime sinusoids at frequencies greater than 0. 1 cps. The orthogonal multiplication technique is a form of Fourier analysis for output data in the form of real and imaginary components of the system output at each input frequency. These data are suitable for graphic display as time-varying Nyquist or Bode plots. Sheridan (1959, 1960a, 1960b) has published such plots showing the 1) shift in closed-loop characteristics as a function of fatigue during a monotonous task followed by an alarm, 2) change in display from compensatory to pursuit and vice versa, 2) change in input signal from random appearing to precognitive and the reverse, and 4) change from simple unity control dynamics to first order control and vice versa. No information about physical characteristics of the operators studied or individual differences in performance was given. The control device consisted of a nearly frictionless joystick and the display was a commercial dual-beam five-inch oscilloscope.

Elkind and Green (1961) have compared the relative merits of the Fourier type analysis, cross-correlation methods, and analog model matching techniques for measuring tracking performance. Although the Fourier type analysis can be inexpensive, it cannot be used to obtain the remnant power spectrum. It requires the use of sinusoids for the input and samples 15 seconds or longer in length, and it may not be used to obtain representations for nonlinear characteristics (other than time variation). Cross-correlation techniques provide remnant data and may not easily be used for continuous "on-line" monitoring. They require long sample lengths but do not distinguish time variation from other sources of remnant.

A method for optimal mimicking techniques has been described by Elkind and Green (1961). They concluded that the method is well suited for linear and nonlinear, time variant and invariant approximations of system measures. The principal advantages are that only very short samples are needed and that in situ signals may be used as the task input. No details regarding cost or relative ease of application to laboratory research were presented.

The time-varying closed-loop transfer characteristics have been measured by Stark, Iida, and Willis (1961) with a somewhat different method. Their subjects rotated a zero order control in response to a pursuit display with a random appearing (sum of three sinusoids) input. The output from the control was fed to a narrow bandpass, Krohnhite filter tuned to select one of the three input sinusoids. The corresponding input sinusoid was recorded simultaneously with the filter output. Phase angle and gain ratio were measured directly from the recordings. The narrowness of the filter resulted in some "ringing" effect which tended to smooth the data and produce a time resolution similar to Sheridan's orthoganol multiplication technique. No data regarding nonlinear characteristics were obtained during single tests. However, Stark, et al., systematically varied the amplitude of one of the three input sinusoids and observed a nearly linear response to these changes.

D. Implications of the Above Review for the Present Study

A large number of studies dealing with the functional characteristics of the upper extremities, perceptual motor skills, and methodology for studying steering type tasks have been reviewed. Certain gross physical characteristics, such as anterior arm reach, have been shown to define operational limitations with respect to some task variables. However, the extensive literature dealing with continuous control tasks is devoid of data relating individual differences in performance to the physical characteristics of the human operator. The amount and types of individual differences in control performance have not been systematically studied as in the present investigation.

Although a wide range of arm strength, size, and range of motion is encountered among supposedly normal populations, the effects of such variations on perceptual motor skills have, with one exception (Duggar, 1963), not been studied. It is inferred that for common tasks the physical requirements are either not limiting or the effects on performance are of no consequence.

The servo-element analogy for describing human performance is enjoying great popularity at the present time. This technique has proven to be particularly suited to the needs of the design engineer concerned with control systems. Because of the specificity of mathematical describing functions and the analogy of certain components of these equations with physical and perceptual properties of the human controller, describing functions may also prove to be an important tool in the study of individual differences in performance. This methodology has been used to study time variations, effects of training, effects of drugs, and the effects of transient aspects of the control dynamics of human performance. It is feasible to use this methodology in an experiment in which the performance of physically impaired persons can be qualitatively and quantitatively compared with that of unimpaired persons during a simulated driving task.

The driving records of the physically impaired or studies of physical impairment and driving do not suggest which, if any, components of the driving task are adversely influenced by any of the many possible impairments. For purposes of this study, it was decided to restrict the experimental investigation to a study of the effects of unilateral amputation on directional control (steering) and braking. Although deficiencies in these skills have not been identified specifically as proximal causes in accidents for either the unimpaired or the physically impaired, the factors which have been identified (speeding, falling asleep, alcohol, failure to yield, etc.) were judged by the authors to be unlikely to be enhanced significantly by orthopedic impairments. However, deficiencies in directional control and braking in an automobile or truck are clearly dangerous, regardless of whether they are mechanical, physiological or psychological in origin.

In order to examine experimentally the influence of amputation on steering capability, the task should be such as to minimize the effects of individual differences in vision, decision processes, or intellectual qualities of the subjects. Since required force and extent of motion vary widely among vehicles (even among those equipped with power steering) and as a function of speed, tire inflation, etc., within a given vehicle, the experiment should include a wide range of control system requirements. Describing functions should be derived as the performance measures.

The study of braking capability can be reduced to a minimum study of speed of movement of the foot from accelerator to brake and the application of slight force.

A fairly large range of individaul differences are anticipated among unselected and poorly trained subjects performing a simulated steering task. Therefore, the tests and data reduction should require only modest amounts of time so that many individuals can be tested. Amputees, professional truck drivers, and non-amputee drivers who do not operate commercial vehicles should be tested. Great care should be taken to assess the size and physical constitution of each subject since differences in size and strength might be expected to produce performance differences or interact with orthopedic impairments.

The following chapters describe the development of equipment, selection of subjects, experimental protocol, and results of a series of experiments developed to meet the above requirements.

V. DEVELOPMENT OF THE EXPERIMENTAL APPARATUS

A. Introduction

The most comprehensive approach for assessing the performance of special sub-groups of the driving population is to measure behavior while operating within a controlled road-vehicle system. However, the expense, time consumption, complexity and inherent risks involved suggest a preliminary and more conservative procedure. A practical approach to the study of the problem is to obtain fundamental data in the laboratory with instruments, such as universal mock-up devices or simulators. This section describes the mechanical, electromechanical, tracking and data-computation features of the simulator developed at the Harvard School of Public Health.

The fundamental design criteria for the simulator were: 1) dimensional duplication of vehicle cab interiors, and 2) adequate adjustability to insure operator comfort.

A tracking task was selected to study the areas of interest described in the preceding section. A large body of relevant literature is available and many actual control tasks are similar to laboratory tracking tasks. Task conditions were designed to minimize performance differences due to display, procedural, and intellectual factors and to emphasize the biomechanical requirements imposed upon the operator's upper extremities.

Design criteria for the tracking equipment were:

a) The task must require application of force and amplitude of movement by the human operator.

b) The task should minimize the effects of training, visual, and intellectual differences among subjects.

c) The equipment must have provisions to allow rapidly altering task variables over a wide range.

d) The performance measures should include both describing function and conventional error data.

B. Mechanical Features of the Vehicle Simulator

The four major components, the seat, dash panel, pedals and steering mechanism of the mock-up were designed and fabricated separately. Three physical requirements were made of each separate component: 1) functional duplication of the truck cab counterpart, 2) remote and/or direct adjustability of the displacements and forces required for activation of control devices, and 3) translational and appropriate angular adjustability. The housing design was contingent upon the requirements of each component. Thus, the support structure is spatially compatible with the full range of the movable components.

The components described above were then appropriately integrated so as to make up the vehicle simulator as used in the experiment. A frontal view of the interior is shown in Figure 1. A lateral view of the seat mechanism is shown in Figure 2 and different views of the foot pedal arrangement are shown in Figures 3 and 4. The lateral and frontal illustrations of the steering wheel mechanism are shown in Figures 5 and 6. Additional information may be found in the papers by Domey and Paterson (1962) and Duggar (1963).

The spatial arrangements of the driver's workspace were designed according to dimensions recommended in a previous study at the Harvard School of Public Health (reproduced in Table 9). The interior of the mock-up was arranged to meet the requirements of a large range of body configurations and to functionally simulate the interior of commercial vehicles.

The seat consisted of a 6-way power unit donated for the project by the Chrysler Corporation. The operator controlled his seat position within ranges of 5" longitudinally, 2" vertically, and 15° rotation about a transverse axis. The electrically-powered unit was mounted on a platform which could be moved longitudinally and vertically, through additional ranges of 9" and 6" respectively. A hand-operated pump which was hydraulically coupled to a power cylinder elevated the platform. The rate of descent of the platform was controlled by throttling the high pressure fluid through a control valve. Longitudinal movement was provided manually through a rack-and-pinion transmission. The seat platform rested on ball bearing tracks and was driven fore or aft by cranking the pinion anchored to the simulator frame. This arrangement permitted coarse adjustments, remotely controlled by the experimenter.

The steering wheel was an 18 inch diameter, standard International Harvester model. To make the wheel angle variable, a universal joint was inserted into the shaft eight inches from the steering wheel. The steering wheel could be locked in any of seven angular positions ranging between 90° and 150°.

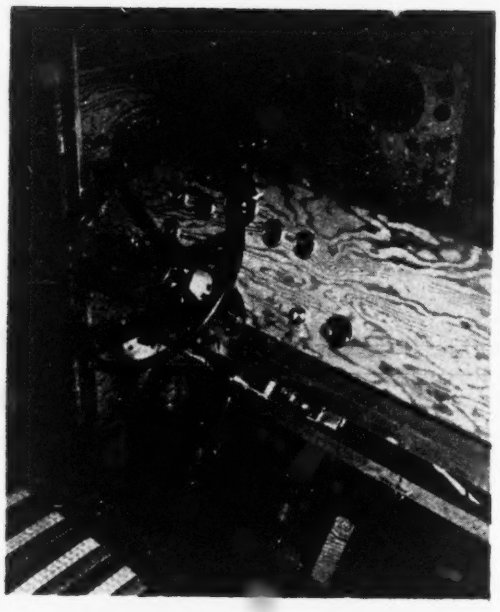


Figure 1 FRONTAL VIEW OF SIMULATED INTERIOR

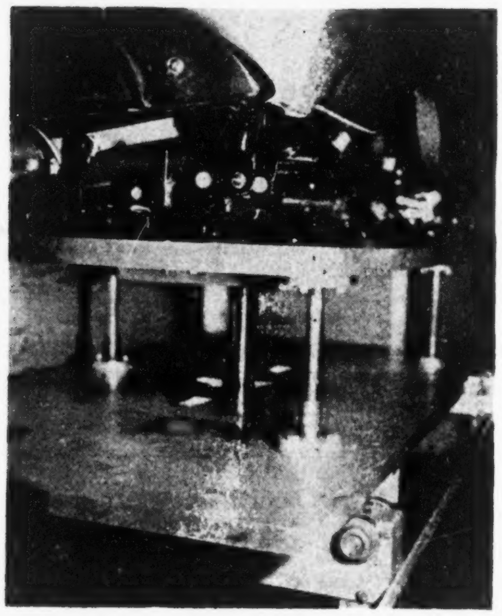


Figure 2 LATERAL VIEW OF SEAT MECHANISM

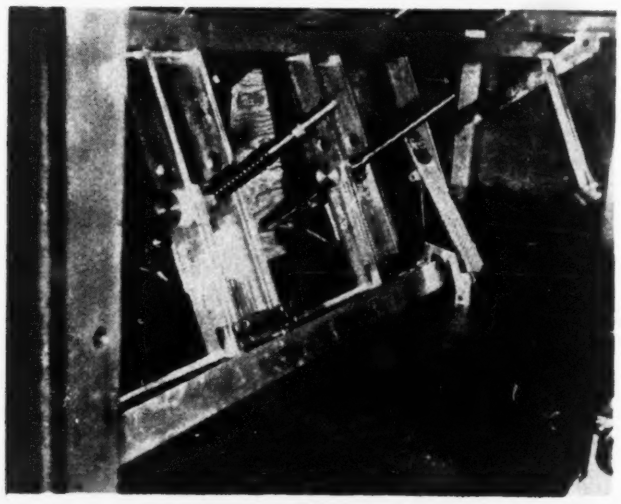


Figure 3 LATERAL VIEW OF FOOT PEDAL ARRANGEMENT

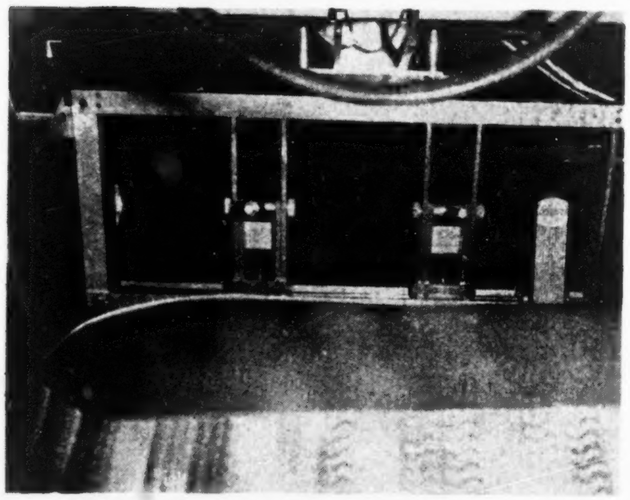


Figure 4 FRONTAL VIEW OF FOOT PEDAL ARRANGEMENT

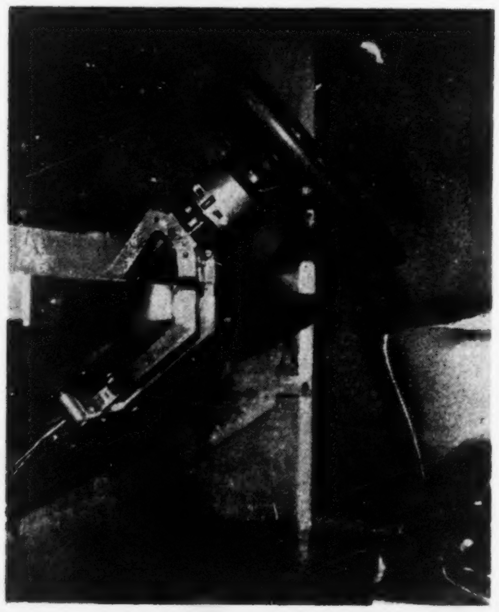


Figure 5 LATERAL VIEW OF STEERING WHEEL MECHANISM

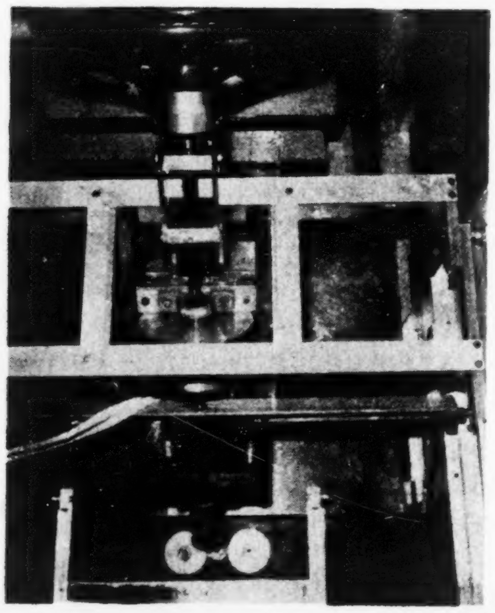


Figure 6 FRONTAL VIEW OF STEERING WHEEL MECHANISM

Table 9

Spatial Dimensions of Cab Simulator

Variable	Range in Simulator(1)	1956 Commercial Vehicle Variations	Recommendations (McFarland, Damon and Stoudt, 1958)
1. Instrument Panel Angle	90°-150°	90°-130°	None
2. Seat Depth	Min. -18''(2)	15.5''-21.75''	18'' - 19''
3. Seat Back Height	Min. -22''(2)	17.5''-21.0''	18'' - 20''
4. Fore and Aft Seat Adjustment	14''	0.00''-6.00''	6.00''
5. Vertical Seat Adjustment	10''	0.00''-3.36''	4.00''
6. Seat Back to Lower Edge of S/W Horizontal Distance	14''-28''	9.26''-16.25''	12'' - 13''
7. Vertical Distance Floor to Lower Edge of S/W	20''-38''	20.5''-27.00''	24.5'' Min.
8. Height of Seat above Floor	12''-30''	13.5''-17.75''	15'' Max.
9. Steering Wheel Angle	15°-75°	20.5°-55.0°	42.5°-48.2°(3)
10. Lower Edge of S/W to Brake Pedal	18''-35''	19.25''-30.5''	26'' Min.
11. Lower Edge of S/W to Clutch Pedal	18''-35''	17.0'' - 27.6''	26'' Min.

(1) Dimensions of the simulator are relative to steering wheel fixed in Lowest-Forward position.

(2) Seat depth and seat back height may be altered with cushions.

(3) Kephart, N. C., and Dunlap, J. W. (1954).

(4) For a complete review of anthropometric data relating to vehicle design see Damon, Stoudt and McFarland, 1966.

The truss-like frame supported the steering assembly at an angle of 45°, approximating the optimum value recommended by Kephart and Dunlap (1954). The frame and steering assembly were supported by ball bearing rollers running on tracks placed on the simulator superstructure. This allowed the entire steering assembly to be moved fore and aft a total of 12 inches.

The steering shaft was supported by two, self-aligning pillow blocks mounted 14 inches apart. The pillow blocks were attached to a framework, supported on axial thrust bearings on lateral tracks. By means of a rack-and-pinion arrangement, the steering unit could be moved six inches in a direction, parallel to the steering shaft. This action effectively telescopes or extends the steering wheel.

Figures 7 through 10 show an amputee driver in various seated positions for obtaining a maximum degree of comfort in performing the steering task.

For purposes of the experiments described in this report, the steering wheel position was locked at an angle of 38° to the vertical, and with a distance of 24 inches separating vertical lines passed through the steering wheel hub and the face of the display apparatus. Vertical and horizontal seat movements were permitted but the seat angle was locked at its midpoint.

C. Tracking Equipment

The tracking equipment consisted of a display, control system, and data computing elements. The display consisted of a random-appearing target course and a pursuit follower presented on a five-inch oscilloscope. Since the experiments were designed to study the influence of physical properties of the upper extremity, a random-appearing target course was used to minimize learning. The pursuit display presentation was used to reduce training time and to minimize the effects of any uncontrolled variations in factors affecting display visibility. A steering wheel control system was used since most persons have had extensive experience in using such a device. The data computing elements provided error scores and describing functions. These performance measures specified the degree to which the operator maintained the target, the pursuit indices in coincidence, and the manner in which this was done.

In Figure 11 a photograph of the tracking equipment is shown as viewed from the driver's seated position. The completed electronic control and recording apparatus is shown in Figure 12.

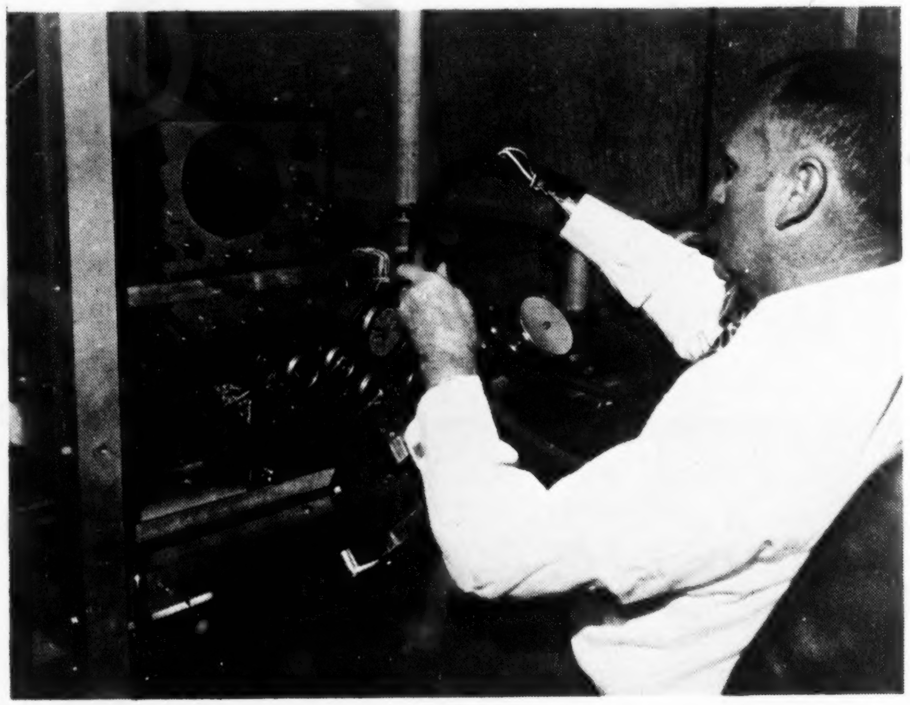


Figure 7. SUBJECT WITH BELOW RIGHT ELBOW AMPUTATION AND HOOK. LEFT ARM SHOWING POST OPERATIVE CONDITION AFTER SURGERY FOR WAR INJURY.

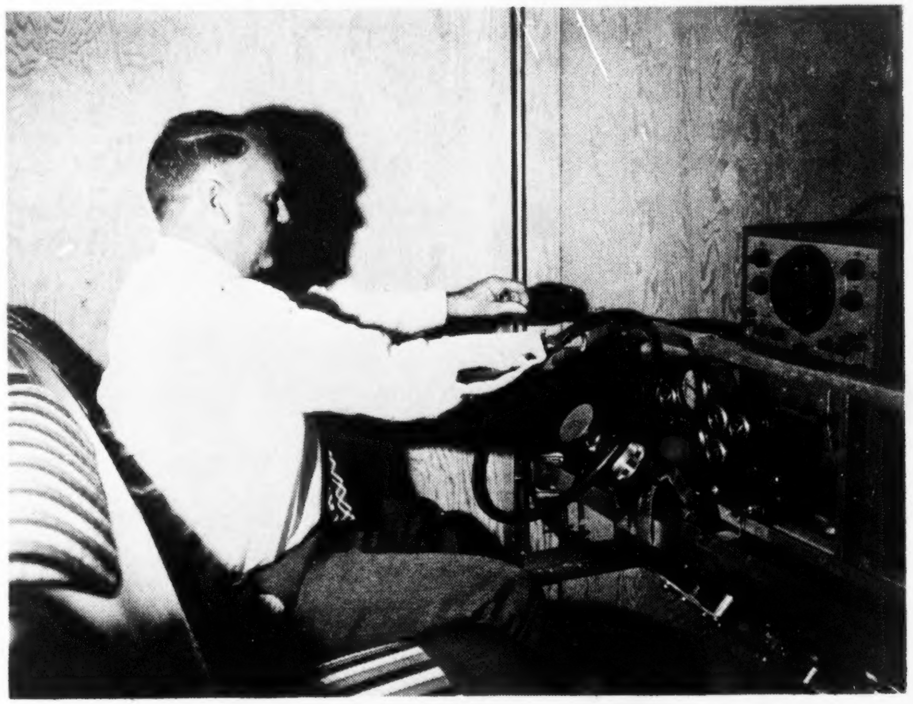


Figure 8. OPERATOR SEATED TOO HIGH AND TOO FAR AWAY FROM THE STEERING WHEEL.

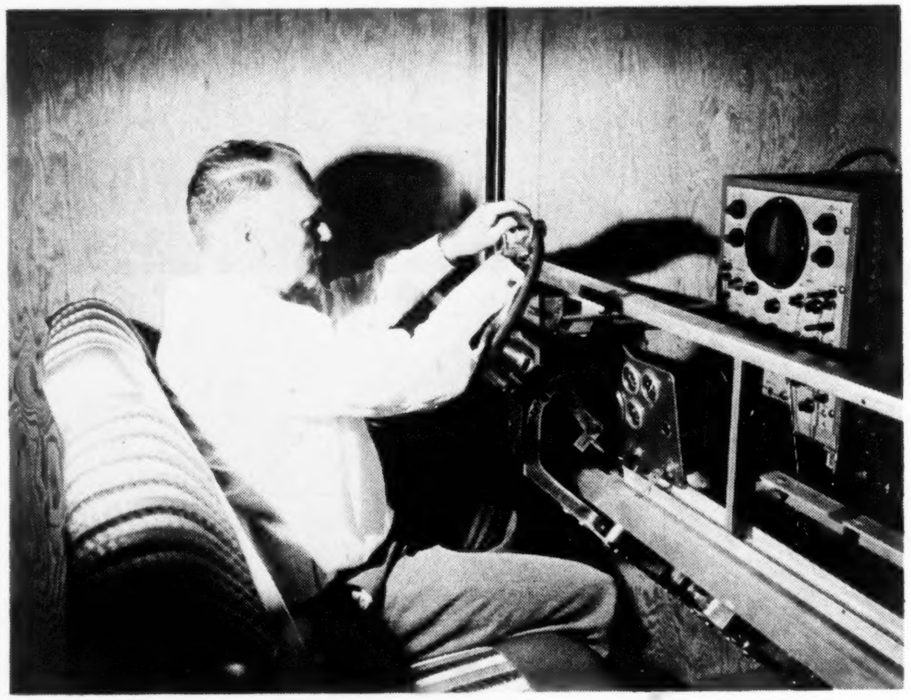


Figure 9. OPERATOR SEATED TOO FAR FORWARD WITH STEERING WHEEL TOO HIGH.

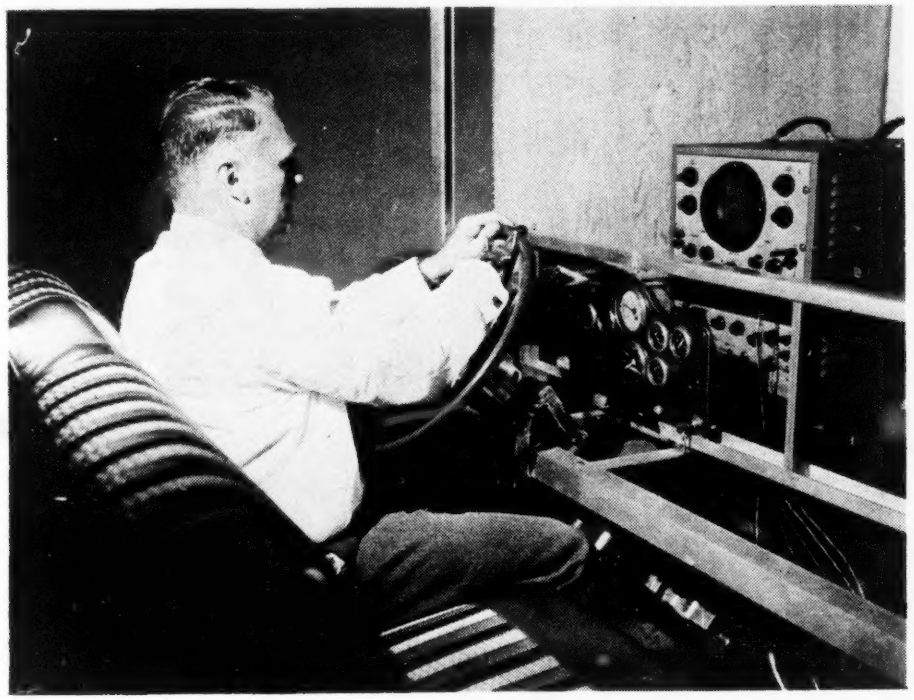


Figure 10. PREFERRED POSITION OF THE OPERATOR.

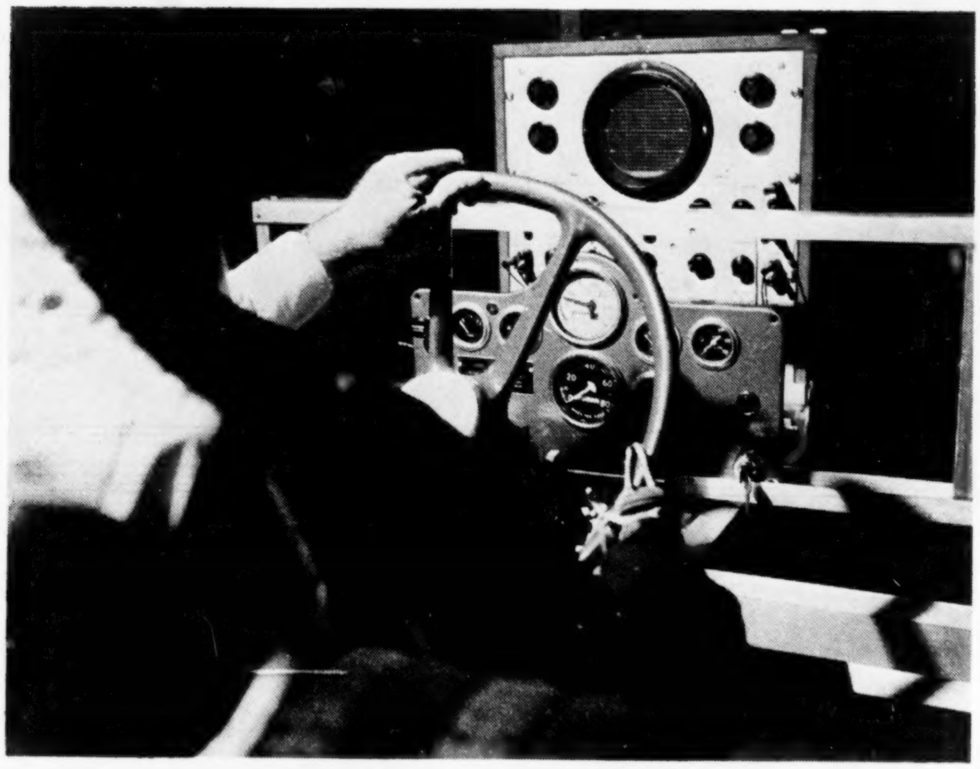


Figure 11. VIEW OF ONE FORM OF VISUAL INPUT TO OPERATOR TAKEN OVER RIGHT SHOULDER.

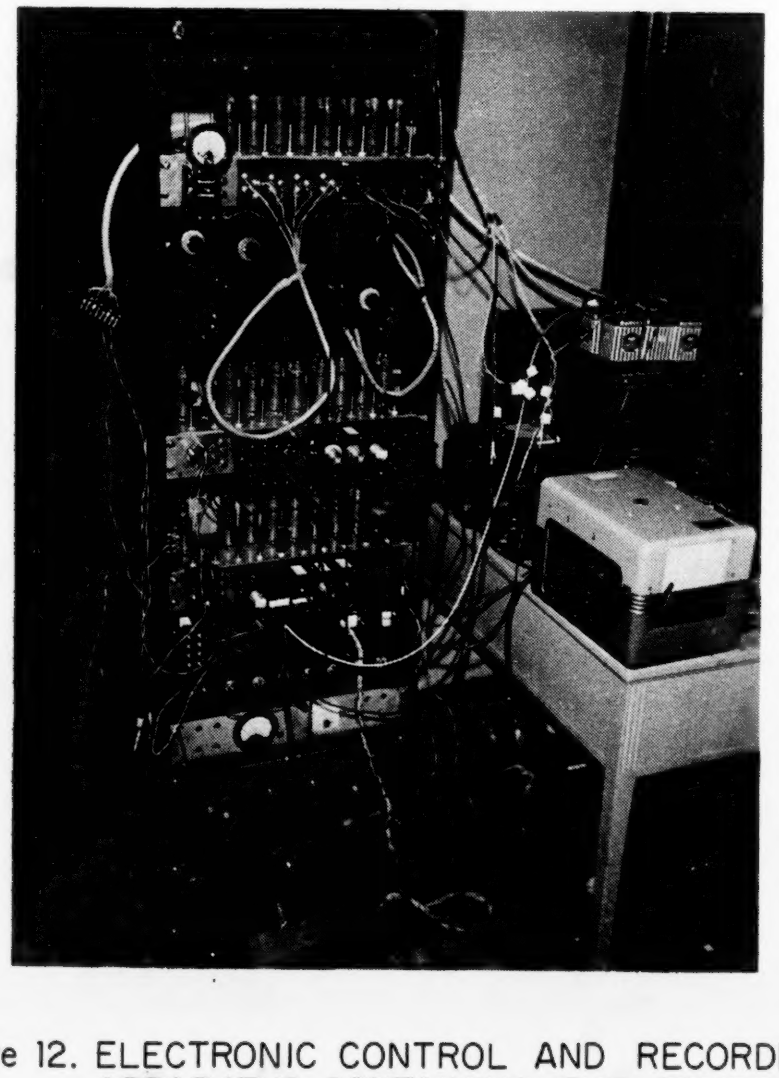


Figure 12. ELECTRONIC CONTROL AND RECORDING APPARATUS CONTAINING THE COMPONENT PARTS SHOWN IN FIG. 1-6.

1. Visual Display

The target course consisted of the sum of four relatively prime-to-one-another sinusoids. This combination was random appearing to the human operator, allowed large changes in the relative amplitudes of the components without destroying the random nature, and facilitated the computation of describing functions. Combinations of frequencies and amplitudes were tested during the pilot studies, and those shown in Figure 13 were selected. Two target courses were chosen, to provide both an "easy" (spectrum 1) and a "hard" (spectrum 2) tracking task. The summed amplitudes of both frequency components shown in Figure 1 equalled 43.5 volts. At a viewing distance of 30 inches and a display sensitivity of 20 volts per inch, the required peak rotational velocities at the eye were only approximately 3^{o} and 4^{o}, respectively.

The target marker was a 0.25 inch dot which traversed the oscilloscope face horizontally. The control follower was a vertical line approximately 0.04 inches wide which spanned the width of the scope face. The objective of the tracking task was to keep the follower and target dot in coincidence. The follower line was generated by an audio frequency oscillator connected to the vertical amplifier of the follower beam on the scope. The target beam was adjusted out of focus to create the 0.25 inch diameter dot.

Figure 14 contains schematics of the two circuits used to generate the target sinusoids. Two fixed frequency oscillators were used to generate the intermediate (0.107 and 0.229 cps) frequencies, while variable frequency oscillators were used for the extreme (0.041 and 0.530 cps) components. These oscillator circuits were selected because they provide, simultaneously, both positive and negative values of the sine and cosine functions. This feature was necessary for the data processing techniques adopted.

Output taps on the oscillators were balanced by trimming potentiometers. Amplitude of each oscillator output was then adjusted to a value which had been calculated on the basis of data processing requirements. In addition, the positive sine function from each oscillator was fed to a coefficient unit (G. A. Philbrick operational amplifiers and passive circuitry were used for all analog operations). Outputs from the coefficient units were adjusted to equal the amplitudes required for the easy and difficult spectrums, then summed and fed to the horizontal amplifier of the target beam on the scope.

2. Control System

A conventional 18 inch steering wheel was used as the control device. Position of the wheel determined the output of a potentiometer driver through a gear chain. Output of the potentiometer went to an integrator and then to the horizontal amplifier of the follower on the

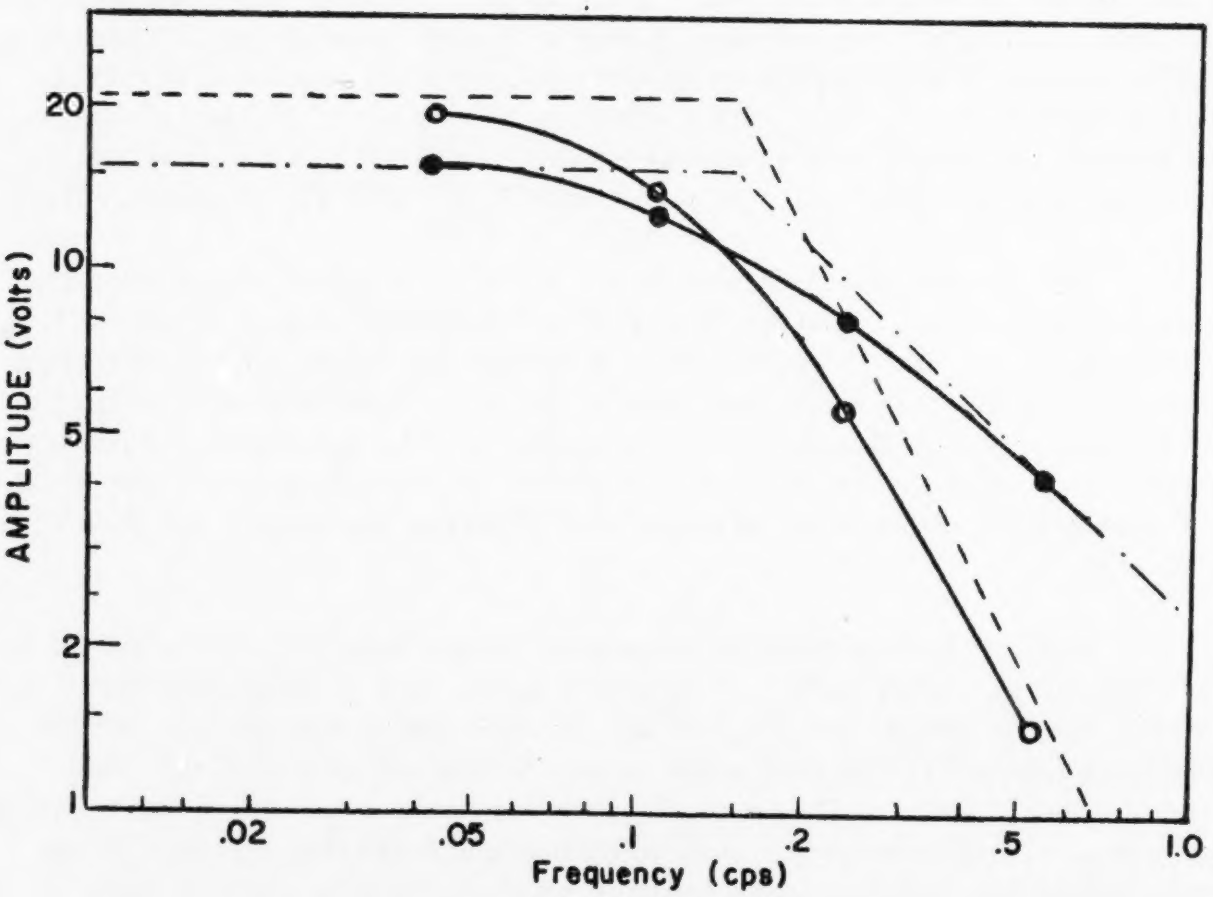
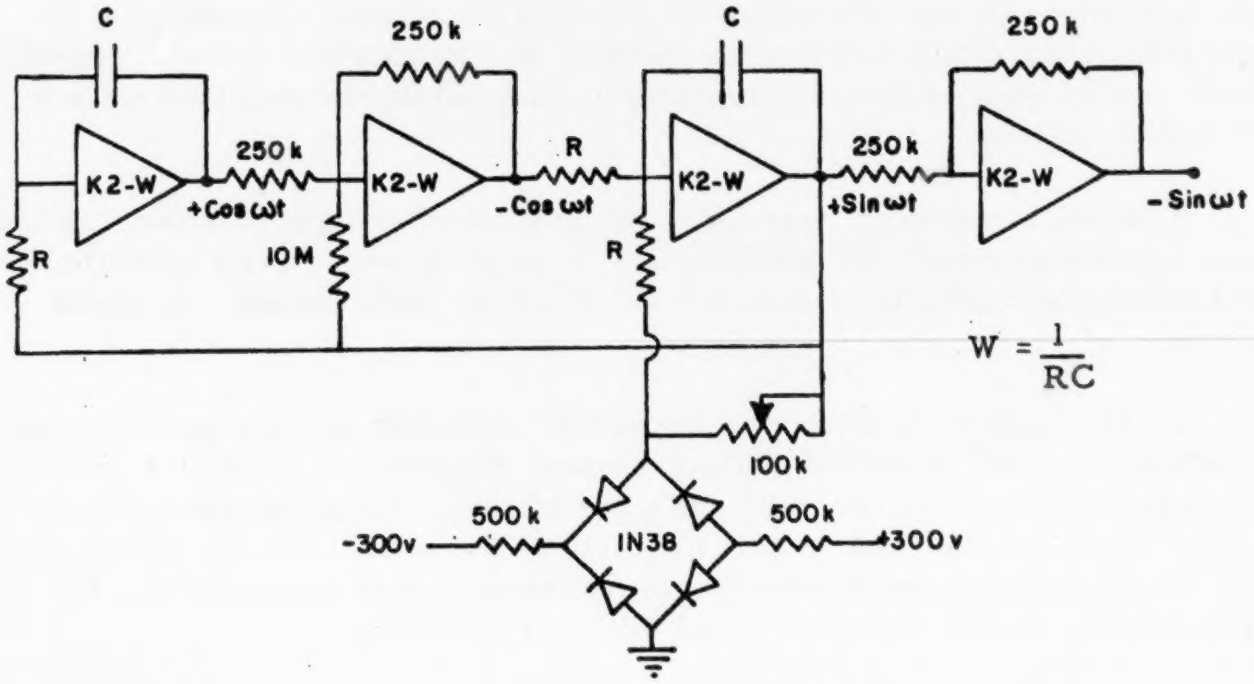
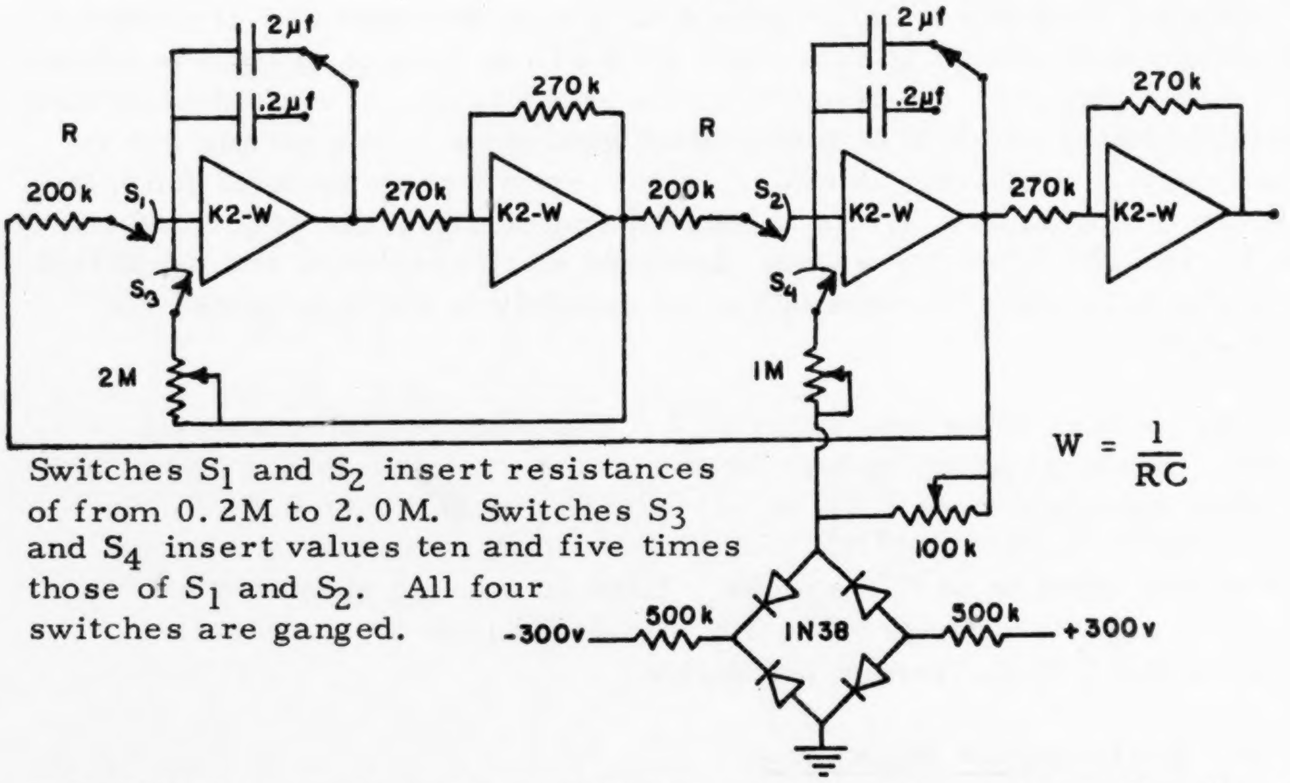


FIGURE 13. Amplitude spectra for two levels of target "difficulty." Voltages selected for the four input frequencies fall within the envelopes of a 6 db/octave (solid circles) and a 12 db/octave (open circles) filter with a corner frequency at 0. 15 cps.



$W = \frac{1}{RC}$



$W = \frac{1}{RC}$

Switches S_1 and S_2 insert resistances of from 0.2M to 2.0M. Switches S_3 and S_4 insert values ten and five times those of S_1 and S_2. All four switches are ganged.

FIGURE 14. Low frequency oscillator circuit schematics. The fixed frequency oscillator (upper schematic) was described in sales bulletin GAP/R from George A. Philbrick Researches, Inc. The variable frequency oscillator (lower schematic) was adapted from Briggs (1960).

oscilloscope, thus constituting a first order control system. A first order control system was used as a means of increasing the wheel acceleration requirements, while not using an excessively high speed target motion. With a first order control system, the operator must move the wheel according to the derivative of the target course. Therefore, all target frequency components greater than one radian per second require control movements of greater amplitude than would be required with a zero order system.

Control sensitivity was adjusted over a 5:1 range by changing the gain of the integrator. An additional 4:1 range in sensitivity was obtained by substitution of alternate gears driving the potentiometer. A wheel sensitivity of 20:1 could be studied.

At the lowest sensitivity, hereafter referred to as a gain of one, approximately 280° of wheel deflection was required to impart a velocity to the follower equal to the peak velocity of the difficult target course, and 200° of deflection was required to equal the peak velocity of the easy task. At the highest sensitivity level where gain was equal to 20, the corresponding values were 14° and 10° respectively.

Control load was simulated by a torque motor mounted directly on the steering wheel shaft. A schematic of the load control system is shown in Figure 15. Position and velocity of the steering wheel were determined by a potentiometer and a d. c. tachometer generator. The torque due to effects of spring centering, damping, and inertia were computed from the position and velocity data by the analog computer elements described in Figure 3. Outputs from the analog elements were combined and amplified, and then fed to the control windings of an amplidyne which powered the torque motor.

The torque motor was rated at 7 ft. lb. torque for continuous operation. Residual damping and inertia of the steering device and attachments were approximately 2 lb. in per radian per sec. and 0.96 lb. in.-sec.^{2}(1.1 kg. cm^2., mass units). Amplidyne-motor time constant was measured and found to be 0.1 second. Load computing elements were continuously adjustable to provide any simulated load or combination of loads within the 7 ft. lb. torque limitation.

3. Performance Measures

The "error", represented by the distance between the follower line and the target dot, was measured by subtracting the target input voltage from the follower input voltage. The resulting error voltage was fed to an absolute value computing circuit and passed to both an integrator and a low-pass filter. Circuits for these computations are shown in Figure 16. The instantaneous absolute value of the error and the

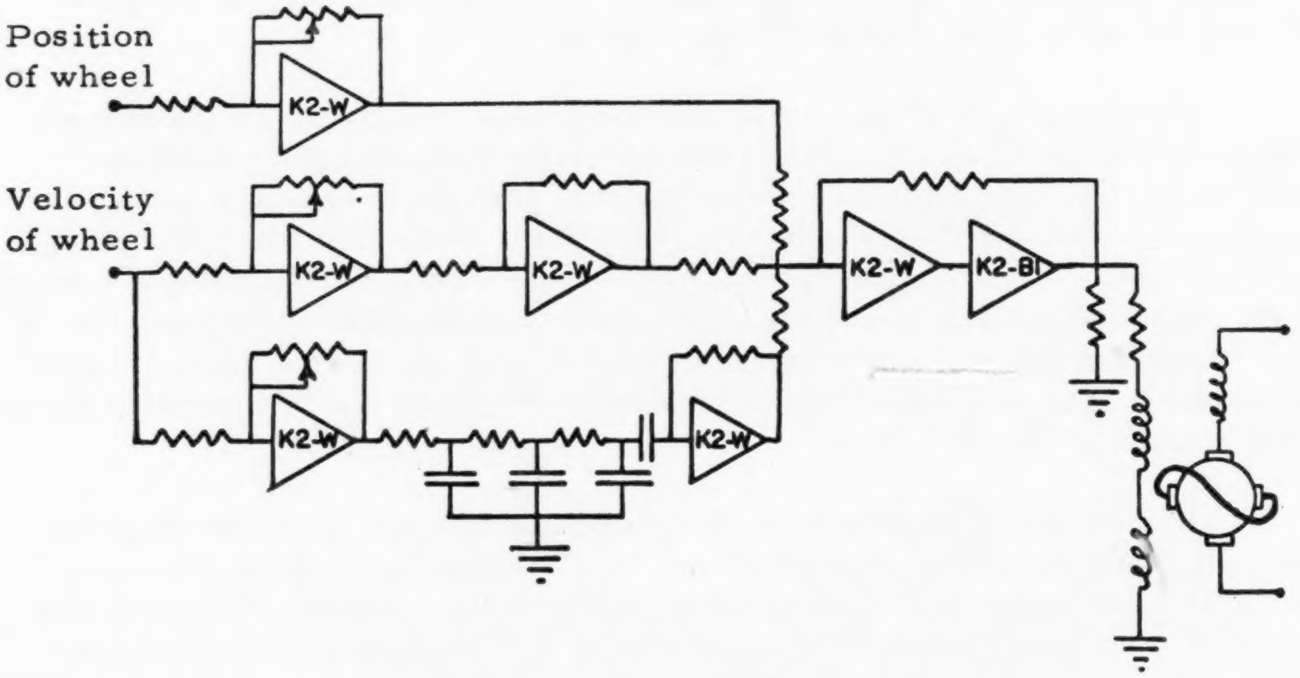


FIGURE 15. Schematic of servo amplifier and amplidyne circuits.

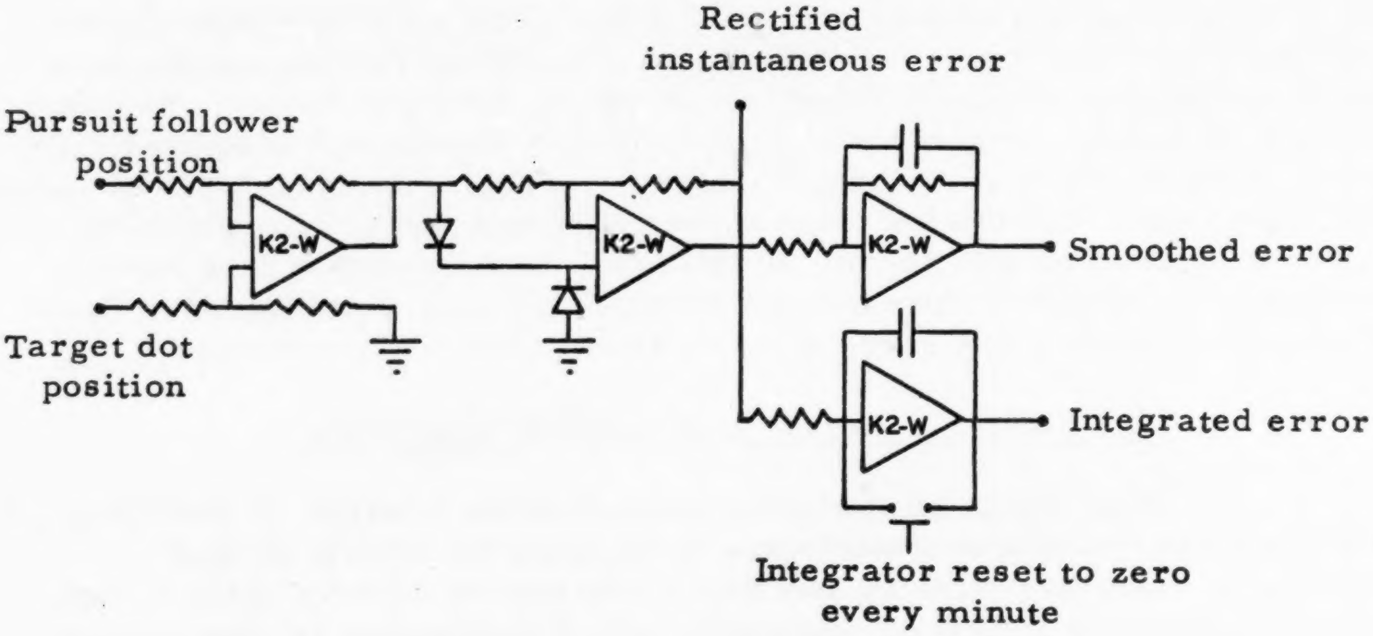


FIGURE 16. Error computing circuits.

"smoothed error", obtained by means of the low-pass filter, were recorded continuously on a Curtiss-Wright four-channel pen recorder. The integrated error was also continuously recorded, but the integrator was reset to zero at one minute intervals.

Time-varying describing functions were computed by Sheridan's orthogonal input multiplication technique (see Appendix B). A block diagram of the essential equipment for this technique appears in Figure 17. The motions of the steering wheel were transmitted through the gear chain to a ten-gang precision potentiometer. Eight of the potentiometer units were used to perform an electromechanical multiplication of each input frequency component (sine and cosine functions) by the wheel movement. The outputs of the potentiometers were fed to low-pass filters which removed the uncorrelated cross-products and noise.

The output voltages from the low-pass filters, representing the real and imaginary components of the closed-loop describing function vector at each frequency, were fed to differential cathode followers and recorded on a Minneapolis-Honeywell 906-B Visicorder. A schematic of one of the low-pass filter and cathode follower units appears in Figure 18. These circuits are slight modifications of those described by Briggs (1960). Experimentally determined filter time-constants were sufficient for rapid response and reduction of amplitude of cross-product contamination of a negligible value.

Facsimiles or typical describing functions and error data appear in Figure 19. Polarities for the various describing function components were selected to minimize interference among the eight traces. Real and imaginary output components at each frequency (described in Appendix B) were recorded by time-sharing the same recorder galvanometer. By using an uneven time distribution between the two components the problem of trace identification was greatly simplified. Error remnant data were obtained by computing the expected error score from the describing function and comparing this score with the actual observed error score.

4. Pilot Studies Using the Experimental Apparatus

A series of pilot studies were directed toward: 1) verifying the utility of tracking methodologies in studying the effects of upper extremity characteristics on steering performance; 2) developing design specifications for improved equipment; and 3) developing an experimental protocol. Subjects used for these studies included seven healthy young men, a right, above elbow amputee equipped with a prothesis, and a commercial driver with moderate to severe myasthenia gravis.

Detailed results of the pilot studies have been reported elsewhere (Duggar, 1963). These data demonstrated that: 1) the performance criteria were sensitive to task variables; 2) the task could be adequately performed continuously for several hours without gross muscular fatigue;

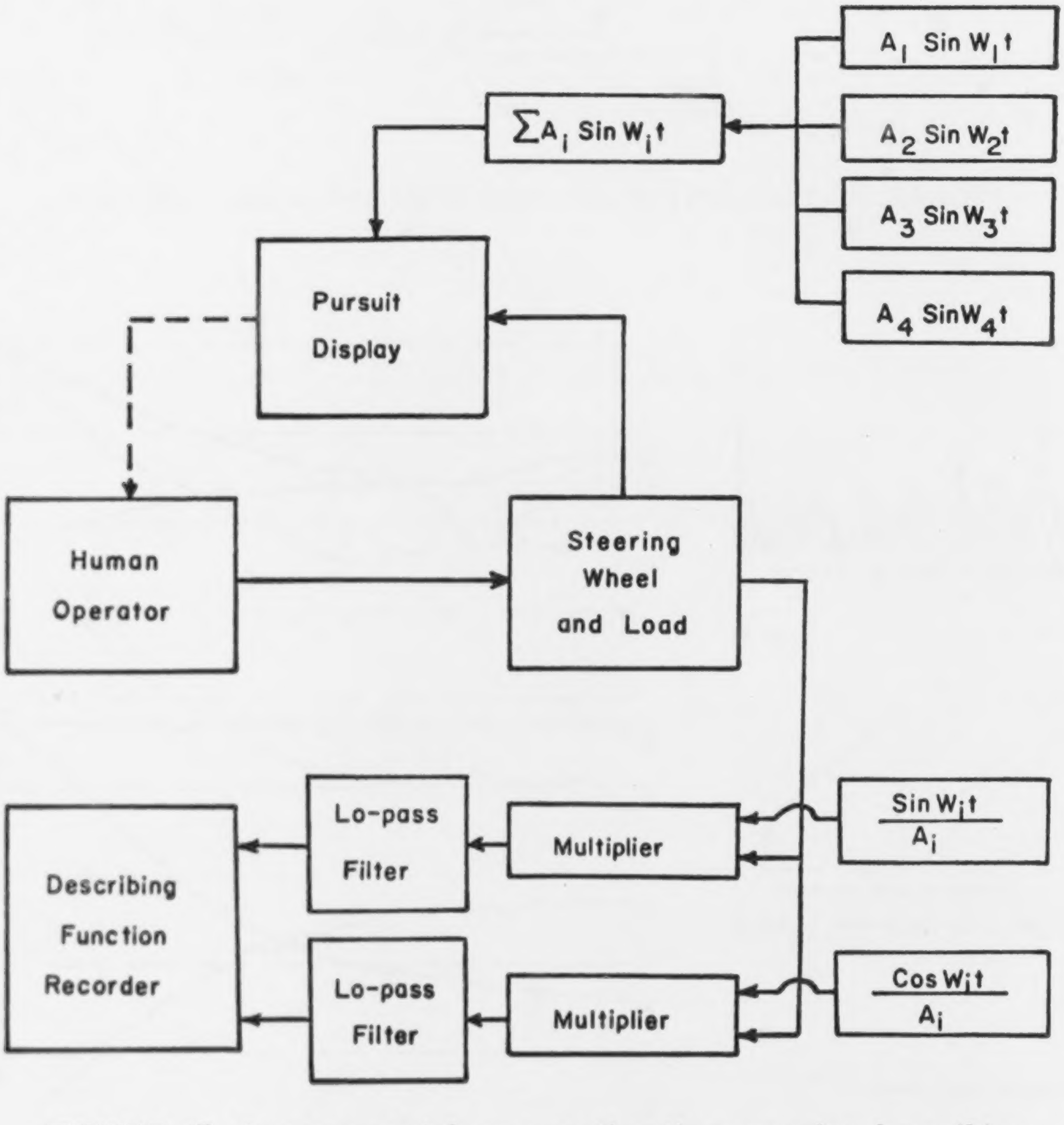


FIGURE 17. Arrangement for computing time-varying describing functions by Sheridan's orthogonal input multiplication technique. Multiplication is performed electromechanically by potentiometers driven by the steering wheel.

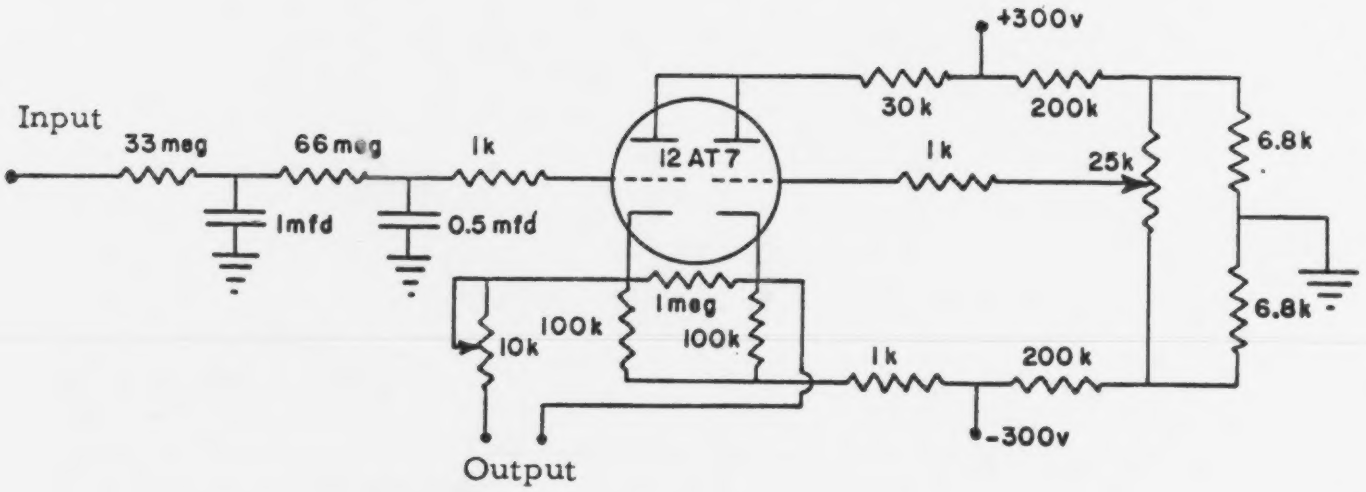
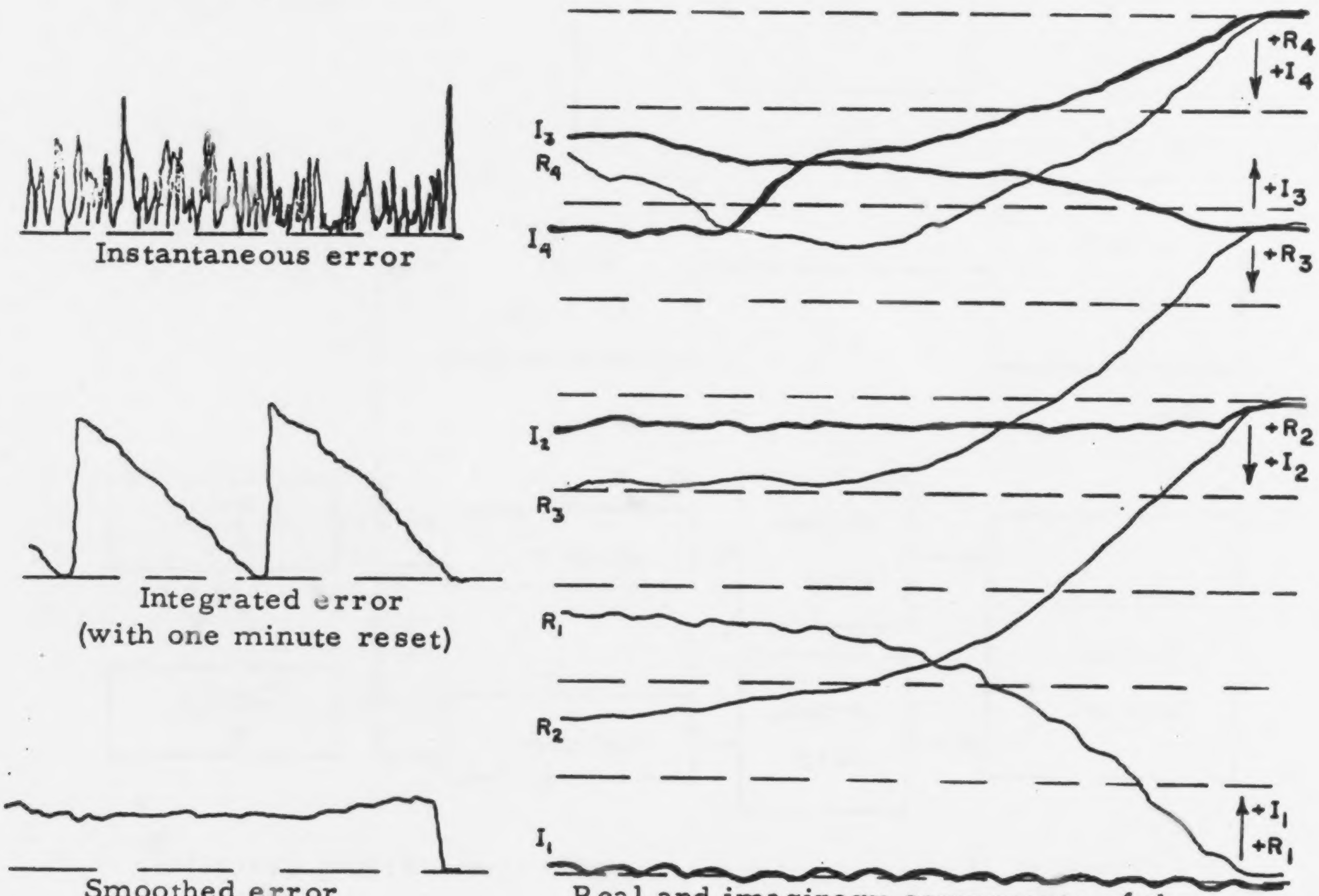


FIGURE 18. Schematic of low-pass filter and cathode follower.



Instantaneous error

Integrated error (with one minute reset)

Smoothed error

Real and imaginary components of the describing functions

FIGURE 19 Facsimiles of typical describing functions and error data. Describing function polarities were selected to minimize interference among traces. Traces move to the left at one inch per minute.

3) early performance differences among subjects were predictive of differences after extensive practice; and 4) the effects of muscular fatigue on performance could be easily distinguished from those due to drowsiness or vigilance decrements. A number of on-the-road measurements made in an instrumented station wagon (provided by the General Motors Corporation) insured that the simulator task parameters overlapped those actually encountered.

VI. EXPERIMENTAL PROGRAM

A. Subject Selection

Complete performance data were obtained from twenty non-commercial, non-amputee subjects (control group), twenty non-amputee, commercial truck drivers (commercial group), and from twenty amputee subjects (amputee group). An abbreviated series of performance tests were used with an additional forty amputee subjects (partial schedule group). In addition, all amputees underwent diagnostic interviews. Methods of subject selection varied between groups, and the groups were not necessarily representative of their populations. Amputees were contacted through the Veteran's Administration, the Amputee Veterans Association of America, Inc., the amputee clinic at the Massachusetts General Hospital, the Liberty Mutual Insurance Company Rehabilitation Center, and the Massachusetts Rehabilitation Commission. Commercial truck drivers were obtained through the Massachusetts State Employment Agency and locals of the Teamsters' Union. The control group included sixteen subjects representing a wide variety of constitutional types, selected to participate in a separate investigation of the influence of physical characteristics of the arms on tracking performance. The control and amputee groups were paid $2. 50 per hour for their participation. For the amputee group this was adjusted to cover a minimum of four hours for each session. Commercial drivers were paid the equivalent of union wages.

In Figure 20 photographs are shown of six subjects who participated in the experiment with upper extremity amputations. Note that the three drivers at the top of the figure have amputations above the elbow and the three subjects in the lower part of the figure have below the elbow amputations. Six different subjects with lower extremity amputations and prostheses are shown in Figure 21.

B. The Amputee Driver - Social Characteristics

Sixty-two amputees volunteered to be interviewed by a psychiatric social worker.* Of these, all but one subject had two interviews, each about one hour. The first few minutes of the first interview were used to

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*Mrs. Helen Domey

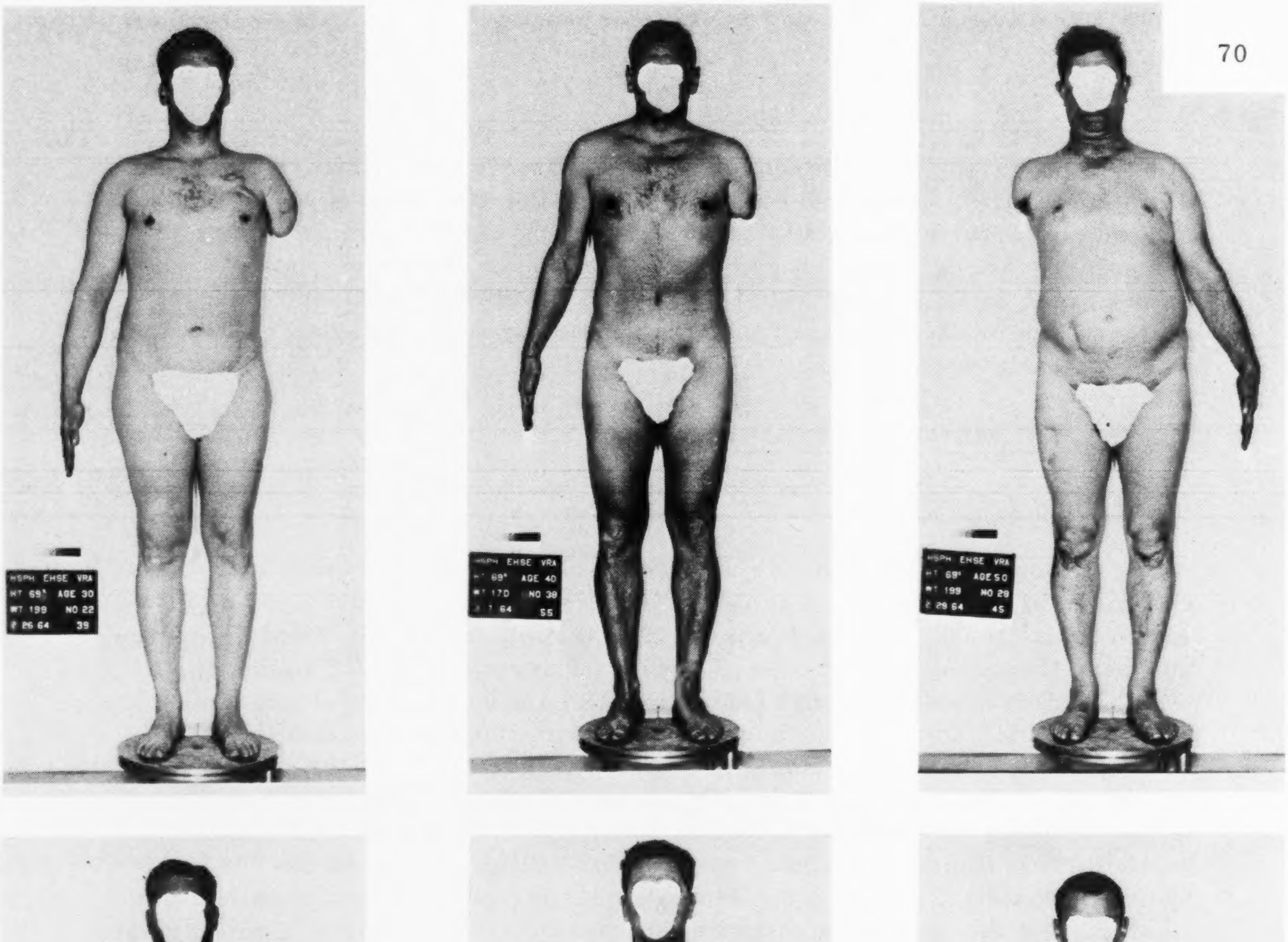

Figure 20 EXAMPLES OF THE KINDS OF UPPER-EXTREMITY AMPUTATIONS, BOTH ABOVE- AND BELOW-ELBOW, OF THE SUBJECTS USED IN THE PRESENT STUDY

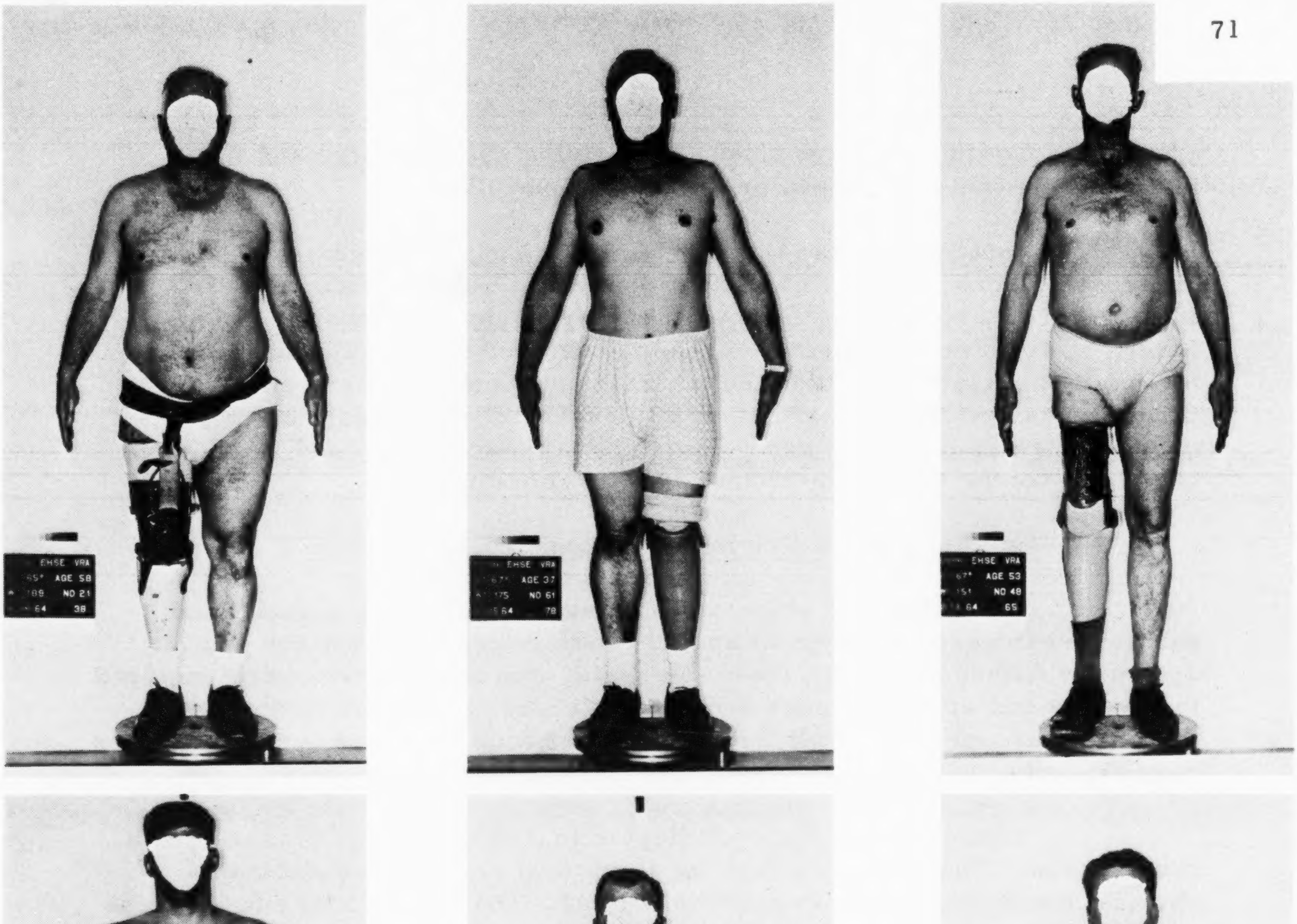

Figure 21. EXAMPLES OF THE LOWER EXTREMITY AMPUTATIONS, AND PROTHESES, OF THE SUBJECTS USED IN THE PRESENT STUDY.

complete a driving questionnaire. The driving questionnaire and the interview schedule have been presented in Appendix A.

The content and behavior of the men during the interviews revealed different reasons for their participation. Some wanted to share their adjustment experiences in the hope that they might help others. Some wanted to express bitterness or unhappiness; seven men expressed the feeling that society owes them better livings because they are amputees. Others were seeking help with current psychological, social, or employment problems; and a few were clearly isolated and lonely and found some relief and comfort from the chance to talk with someone.

1. Summary of the Driving Questionnaire

Sixty of the 62 amputees obtained their driving permits and subsequent licenses between 17 and 21 years of age. All but two had driven for fifteen or more years. Men with arm amputations were required to have special steering knobs and automatic transmissions in their cars. Although only one man in the leg amputation group reported special licenses requirements, all had automatic transmissions in their vehicles.

Fifty-seven subjects indicated that driving is a pleasure and a convenience. The other five (all leg amputees) reported considerable physical disability and discomfort in driving. Driving as a way to increase mobility was not mentioned by anyone with leg amputations.

The amount of driving in the group ranged from 500 to 70,000 miles annually. An arm amputee who only uses his car to go back and forth to work reported the lowest mileage. The highest was reported by a salesman with a leg amputation. Twenty of the 62 men drove primarily in the country; the rest participated equally in country and city driving.

All but three subjects expressed no difficulty in handling an automobile. Of these three, two were arm amputees who could not manage without special vehicular conveniences. One leg amputee indicated that pain sometimes interferes with his driving ability. Of the men with arm amputations, four reported they had been in minor accidents (not serious enough to report) and the rest had had none. Four of the leg amputees had caused accidents serious enough to be reported.

Twenty-seven of the 62 men had commercial driving experience and consider themselves competent to continue to do it now. Forty-nine of the amputees believe that men with arm or leg amputations should be allowed to drive trucks in all sizes and weights. One other feels that a man with an arm or leg amputation would be "pressing his luck if he tried," and a second stated that anyone with an amputation should not be allowed to be a commercial driver. The rest believe that either leg amputations above the knee or any leg amputation should prohibit a person from driving commercially.

2. Findings and Interpretation of the Interviews

a. Cause of amputations: Thirty-four men had accidents or combat injuries while on duty in military service. Five other military accidents occurred while the men were off duty. Industrial accidents accounted for twelve amputations, childhood accidents for five, illness for three and personal accidents in adulthood for three.

One of the personal, adult accidents and one of the childhood accidents were attributed to family circumstances; both were the result of dangerous situations which emerged after each man had become angry with a member of his family.

All of the men who suffered industrial accidents blamed themselves, fatigue or lack of adequate safety measures. The military men injured in combat had no premonition of the injury but had expected it. Those hurt off duty had no premonition and no expectation that they would be hurt.

b. Age, marital status, residence: Ages ranged from twenty to sixty. Forty-eight of the men were married and had children; six of these were remarried. Six were married but had no children; three had been divorced and were living alone. Five of the subjects were single.

Eleven subjects lived in Greater Boston, the others lived in suburbs, small towns or large industrial centers at least fifteen miles away.

Forty-two men owned or were building their own homes. Fifteen others were renting houses or duplexes. Four lived in apartments or rooms. One young man lived with his parents.

Seven subjects were the only children in their families of origin, and ten had only one or two siblings. Three had been adopted at an early age and did not know their siblings or other relatives until they were older. Six subjects had lived with their divorced mothers.

One subject came from the upper middle class, ten from the lower middle class and the rest from various ranks of the lower class.

c. Education: Educational achievement ranged from seventh grade through advanced college degrees. Thirteen men had dropped out of high school and had no further training, six others dropped out of high school but had completed some training for semiskilled jobs, and eleven others had completed high school. Twenty-three of the men had had some college, semiskilled, or other technical training. Three more completed college, two others were currently working toward advanced degrees, and four held professional degrees.

In view of the fact that 34 of these amputees lost their limbs in World War II and were eligible for essentially free education, the educational level of this sample was considered low. Eight of the veterans took their failure to complete their schooling as an indication of their immaturity at the time of their accidents. The four who had completed college did so in the last few years while they were working full time. All four of the men who had plans for further education had actually started on their programs.

d. Employment: Two subjects were lawyers, one a professor, one a teacher, and one a physician. One owned two factories, one was an unusually successful electronics salesman, and several held important supervisory or managerial positions in large industries. Nine held semi-professional positions, nineteen held clerical positions in some branch of the Federal government. One was a full-time student who held a summer job requiring technical skills. Two were unemployed by choice; one was in temporary ill health and the other was changing jobs. The rest of the men held semiskilled or unskilled jobs; two drove trucks, one within an industrial area the other on the highway.

The government workers chose their jobs for their security and ease. Most of these jobs were at night, required little or no communication with fellow workers and were intellectually undemanding.

All of the arm amputees mentioned difficulties finding employment. Two experienced severe rejection by prospective employers. Because they need to remain seated, men with leg amputations also had difficulty finding suitable work. All of the men stated that they had to compensate for their physical disabilities.

Only five subjects believed that their disability had effected their choice of work. The military amputees, for the most part, had not worked very much before they entered the service.

Following amputation, only four men had employment retraining. All were arm amputees, two of whom also had injuries to the other hand; and all had taken courses in television and radio repairs.

e. The amputation and medical care: The majority of military injuries were of the guillotine type; and most men in military accidents or combat were amputated shortly after their injuries. There were four cases in which amputation became necessary because osteomyelitis had occurred. Phantom limb experiences were reported by all subjects, and still occur for many; arm amputees were still reaching for dropped objects with their hooks or stumps. Leg amputees attributed their current phantom limb experiences to fatigue. All of these experiences took place at night, and a few of them have been regular, monthly occurrences.

Hospital ranged from a few days to three years. Men in industrial accidents stayed in the hospital for shorter periods of time than those with military or childhood accidents or illnesses. In general, doctors and nurses were cited as being most helpful, but military men also included their fellow patients. Discharge plans were usually initiated by the doctor.

All subjects injured in military service were in good physical condition when they left the hospital. All had been fitted for the regulation prosthesis and had been taught how to use it. Arm amputees were not discharged until they could dress themselves and otherwise care for themselves.

The prosthesis is used in varying ways. It is required on the job, it is worn; otherwise, arm amputees prefer to function with one hand. Prosthesis fitted to below-elbow amputations are reported to be fairly comfortable; above-elbow prostheses are heavy and cumbersome. All of the leg amputees find their prosthesis uncomfortable; but, again, the place of the amputation is directly related to the degree of comfort.

One industrial accident victim and one childhood accident victim wear cosmetic hands. One wears a large ring on his cosmetic finger; the other wears his hand only for business and prefers his "romantically empty sleeve" at other times. Two men who had had illnesses resulting in leg amputations wear no prosthesis but use crutches for their greater security of movement.

No veterans use the designated Federal amputation clinic to any great extent, and several use it only to reverify their eligibility for benefits. The reasons given for this preference for private help are: 1) the longer waiting periods at Veterans Administration hospitals; 2) the clinic personnel tend to be skeptical about the patients' suffering; 3) the real or imagined lack of skill.

Most of the subjects did not have adequate help after they left the hospital; and there is a clear need for some system of follow-up care and education.

f. Social situation: The few men who were married before their amputations found their wives to be helpful during their adjustment periods. Four who showed marked dependency needs brought their wives to the second interview, but most talked about their wives in casual terms. All who had children showed pictures of them, talked about each child and their plans. Three of the men who were either unmarried or without children were enthusiastic about their voluntary service to young boys. The four wives who came to the second interviews had a warm, managerial approach to their husbands, indicating that they always did things together.

All of the men with military injuries had belonged to the Veterans' Amputee Association. Only six had remained active in it, and these men used the Association primarily to obtain as many benefits as possible.

Many of the men with leg amputations confine their social life to visiting relatives and friends and to watching television. The professionals and semi-professionals lead full and apparently rewarding social lives; but seven men report no social activity at all.

Swimming was one of the favorite forms of recreation, and woodworking with model or full-size boats the hobby of several. Men with children enjoyed such outdoor activities as walks, picnics, and fishing with their young ones.

Only the professionals were active in community government. Two unskilled laborers had volunteered for several years in a neighborhood community center, and a third managed a religiously-sponsored youth bugle corps. All but one subject felt they were doing as much as they could.

g. Emotional reaction to amputation: There were a wide range of immediate reactions to the amputation: relief from pain or illness; shock over the loss; joy that they were alive; thankful that they were in better shape than the fellow in the next bed; apprehension about the future. Most of the subjects reported a period of depression, one to three weeks after the amputation. Doctors seemed to provide the most help in overcoming these depressions; although, in two cases, friends were the most helpful.

Although most of the men were willing to review their situations, there were striking differences among them. For example, all except two of the subjects with combat injuries detailed their experiences with the most minute data (date, exact time in seconds, weather, and so on) as if the accident had occurred yesterday (when, in fact, it was at least twenty years before). The two exceptions spoke only of general circumstances. Industrial accident victims concentreated on the length of time between injury and rescue. The subjects injured in childhood emphasized their early compensatory activities; and those with illness spoke of relief from pain.

h. Summary of personality and behavior dynamics: Although many different kinds of personality types were represented in this sample, certain qualities were characteristic. Regardless of how or when it occurred, the greatest effect of amputation was a decided increase in personal motivation to succeed. Secondly, the kind of adjustment made to amputation was clearly related to personality development and personal experiences. For example, the amount of stature and self-reliance, as indicated by stable family life, economic and social status, educational achievement, was related to how well the subject could meet his new situation.

The degree of ego strength prior to amputation seems to determine the ability to adjust. Four men with varying degrees of intelligence, backgrounds, and levels of education had such strong motivations to succeed that they have been able to lead happy lives. Three of them grew up in extreme poverty, and only one had any stability in his early life. Four of the subjects were angry or guilty about their amputations. All four have had difficulty controlling their anger of hostility but found ways of compensating for it.

Three of the amputees carry their plastic arms around in suitcases and were more interested in the current mechanical improvements than in their utility. All have several prostheses to leave in convenient places where they work. The prostheses are treated as separate entities, removed from the amputee himself. These men were jovial, talkative, full of ideas about a successful future, and they were functioning adequately.

Seven of the veterans spent most of their time looking for ways to get more help. to avoid work, and to discourage any proferred help. They participated for the financial remuneration alone and openly demanded more than had been agreed upon.

If acting-out was a characteristic problem-solving method before the amputation, it remained characteristic afterwards. One of these spoke of needing help with his behavior. A second felt that his behavior would improve as he matured. In these cases, the amputation provided an excuse not to control behavior.

Denial helped some men in unusual ways. One leg amputee still skis, several swim in the ocean without companions, others with missing legs dance until their stumps become irritated and inflamed. Some pride themselves on their handiness in performing home repairs.

Chronic dependency and depression characterized another group. They gave up all hope for self-development and growth when their accident or illness occurred. Two have experienced complete role reversal in reaction to feeling of having lost masculinity.

Anxiety was present in almost every interview, some of it from the interview experience itself and some from the traumatic nature of the subject matter.

No psychiatric data were collected for the non-amputee samples.

C. The Subjects - Physical Characteristics

This description of the physical characteristics of the subjects has a two-fold purpose. First, it describes an amputee population anthropometrically. To achieve optimum performance, close integration of man with machine is especially important. Equipment used by amputees--vehicles, tools, workspaces, and perhaps, most important, prosthetic devices--should be designed in terms of each amputee's unique physical characteristics.

Secondly, these data are useful in investigating possible relationships of human morphology to physical performance. It is reasonable to assume that the way in which a person performs on simulated (or real) driving tasks is related to his physical characteristics. Therefore, it is particularly important in the present study to determine how similar the amputee and control populations are in their basic morphologies. For example, if one physical type predominates in either group, the comparison of the results must take it into account.

In the present study, 80 different measurements relating to body size, structure and composition were taken on each of 30 upper extremity amputees and 29 lower extremity amputees. These data are given in Table 10.

For the non-amputee controls used in the study, comparable anthropometric data are available on only 15 subjects. Anthropometric data are incomplete for some non-amputee subjects because they were either unable to return for a complete anthropometric study or were participants in an earlier investigation for which certain data were not collected. However, 12 basic measurements have been taken on 15 additional non-amputees used in the study, making a total control population of 30 on which partial anthropometry is available. These 12 measurements for height, weight, several body lengths, a breadth, measures of body fat and "constitutional type" are especially appropriate for comparative purposes. Given in Table 11 are means and standard deviations for both amputee and non-amputee groups, and the mean values from a representative sample of the general U. S. civilian population for 6 of these variables. The differences between the non-amputee controls

Table 10

The Anthropometric Characteristics of the Amputee Group

	Upper Extremity Amputees				Lower Extremity Amputees			
Variables (in mm, except as noted)	N	Mean ±	S. E.	S. D.	N	Mean ±	S. E.	S. D.
Age (years)	29	39.5 ±	2.0	11.0	30	42.9 ±	1.1	6.3
Weight (pounds)	29	174.3	6.0	32.3	30	182.6	5.3	29.1
Stature	29	1725	10.0	54.0	30	1730	14.1	77.1
Span	-	-	-	-	28	1711	61.3	324.2
Anterior arm reach	29	833	5.1	27.4	21	843	10.0	45.6
Span akimbo	14	924	11.0	41.1	29	941	7.9	42.6
Upper arm length	29	334	2.3	12.4	30	339	3.0	16.5
Radius length	29	261	2.3	12.5	30	259	2.7	14.8
Tibia length	29	395	4.0	21.6	26	388	4.8	24.5
Foot length	29	269	2.2	12.1	7	275	6.6	17.5
Foot breadth	29	100	0.7	3.8	7	102	3.2	8.4
Biacromial breadth	29	397	3.6	19.6	30	397	4.0	21.8
Bi-iliac breadth	29	293	3.7	20.1	24	291	4.0	19.5
Bitrochanteric breadth	29	330	4.0	21.5	9	321	5.8	17.3
Chest breadth	29	292	4.5	24.4	29	300	4.8	26.1
Chest depth	29	225	5.0	27.1	29	233	4.8	21.6
Abdomen depth	29	251	7.8	41.8	27	262	5.4	28.1
Ankle breadth, right	29	73	0.7	3.8	21	71	1.0	4.5
Ankle breadth, left	18	73	1.0	4.1	9	73	1.2	3.7
Shoulder circumference	28	1156	17.2	90.9	30	1200	15.4	84.4
Chest circumference, normal	29	990	17.6	94.9	30	1042	14.8	81.1
Chest circumference, maximum	29	1017	17.5	94.1	30	1067	15.2	83.1
Chest circumference, minimum	29	979	17.6	95.0	30	1035	14.7	80.4
Abdomen circumference, umbilicus	29	934	23.2	122.5	26	969	17.5	87.5
Upper arm circumference	29	324	6.4	34.6	29	330	4.5	24.4
Biceps circumference, right	14	348	7.8	29.2	29	351	4.8	25.7
Biceps circumference, left	17	346	8.3	34.2	9	354	7.3	21.9
Forearm circumference, right	12	288	6.2	21.5	29	285	3.4	18.1
Forearm circumference, left	17	283	4.9	20.2	9	281	3.7	11.1
Wrist circumference, proximal, right	12	175	3.3	11.4	29	176	2.2	11.6

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Table 10 (continued)

The Anthropometric Characteristics of the Amputee Group

	Upper Extremity Amputees				Lower Extremity Amputees			
Variables (in mm, except as noted)	N	Mean ± S. E.		S. D.	N	Mean ± S. E.		S. D.
Wrist circumference, proximal,left	15	177	2.7	10.4	9	173	2.8	8.4
Thigh circumference, right	27	579	11.6	60.4	20	593	10.9	48.6
Thigh circumference, left	20	577	14.1	63.2	6	628	17.9	44.0
Calf circumference, right	27	375	5.3	27.8	20	386	6.8	30.5
Calf circumference, left	20	372	6.6	29.3	5	409	14.7	32.8
Ankle circumference, right	27	227	3.1	16.3	20	212	8.8	39.3
Ankle circumference, left	20	227	3.4	15.1	5	237	5.7	12.7
Sitting height, normal	29	855	7.9	42.3	30	866	7.1	39.0
Sitting height, erect	29	904	6.4	34.2	30	914	6.2	33.9
Sitting eye height	29	794	6.7	36.2	30	804	5.6	30.5
Shoulder height	29	612	4.9	26.5	30	618	5.0	27.1
Trunk height	29	602	5.0	26.8	30	612	5.1	28.1
Knee height	29	539	4.4	23.6	28	538	6.1	32.4
Shoulder-elbow length	28	369	2.6	13.9	30	372	3.0	16.6
Elbow-middle finger length	29	477	3.3	18.0	30	471	4.0	21.6
Buttock-knee length	29	596	4.5	24.0	28	604	6.4	33.8
Bideltoid breadth	27	473	6.0	31.3	30	487	5.9	32.1
Elbow-elbow breadth	17	470	14.5	59.9	30	487	7.6	41.9
Hip breadth	29	373	5.9	32.0	24	382	7.3	35.8
Knee-to-knee breadth	28	200	2.7	14.5	-	-	-	-
Tibia breadth, right	28	90	1.2	6.6	19	88	1.2	5.3
Tibia breadth, left	18	91	1.7	7.3	9	91	1.9	5.6
Femur breadth, right	28	96	1.2	6.1	19	95	1.2	5.1
Femur breadth, left	18	96	1.4	5.9	9	97	1.2	3.5
Humerus breadth, right	15	71	0.6	2.5	27	70	0.6	3.0
Humerus breadth, left	14	70	1.1	4.2	8	68	0.9	2.7
Wrist breadth, right	15	57	0.6	2.3	27	57	0.7	3.5
Wrist breadth, left	13	57	1.0	3.5	8	56	0.6	1.8
Hand length	29	191	1.6	8.5	30	187	1.6	8.8
Hand breadth at metacarpale	29	85	0.7	3.9	30	85	1.3	6.9

Table 10 (continued)

The Anthropometric Characteristics of the Amputee Group

Variables (in mm, except as noted)	Upper Extremity Amputees N	Mean	± S.E.	S.D.	Lower Extremity Amputees N	Mean	± S.E.	S.D.
Hand breadth at thumb	29	100	1.0	5.3	30	98	0.9	4.9
Head circumference	29	573	2.6	13.9	29	577	3.5	19.0
Head height	29	125	1.2	6.3	30	127	1.2	6.8
Head length	29	196	0.9	4.8	30	196	1.4	7.7
Head breadth	29	153	0.9	5.1	30	154	1.1	6.0
Minimum frontal diameter	29	107	0.8	4.1	30	107	1.0	5.7
Bizygometic diameter	29	142	1.0	5.2	30	141	1.1	6.1
Bigonial diameter	29	108	0.9	4.9	29	108	1.2	6.3
Face length	29	120	1.1	5.7	30	122	1.1	6.2
Nose length	29	51	0.6	3.1	30	51	0.6	3.3
Nose breadth	29	37	0.8	4.5	30	37	0.6	3.3
Triceps skinfold	29	12	0.9	5.0	30	14	1.0	5.5
Subscapular skinfold	29	20	1.9	10.4	30	21	1.6	9.0
Suprailiac skinfold	29	24	2.0	10.8	30	26	1.4	7.6
Thigh skinfold	29	18	1.4	7.5	24	18	1.1	5.2
Knee skinfold	29	12	1.1	5.9	25	10	0.6	3.2
Grip strength, right (kg.)	14	68	2.8	10.6	29	68	2.2	11.7
Grip strength, left (kg.)	11	63	2.7	9.0	30	66	2.2	11.9
Endomorphy	26	3.6	0.2	1.2	29	3.9	0.2	0.9
Mesomorphy	26	4.5	0.2	0.8	29	4.3	0.1	0.7
Ectomorphy	26	2.7	0.2	1.0	29	2.6	0.2	0.8

Table 11

Selected Physical Measurements of the Amputees and the Non-Amputees and the General U. S. Population

Measurement (in inches except as noted)	General U. S. Population from National Health Survey (Stoudt et al, 1965)			Non-Amputee Controls from Present Study			Upper Extremity Amputees from Present Study			Lower Extremity Amputees from Present Study		
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.
Age (years)	1,487	35-44*	-	30	27.7+1.0	5.4	29	39.5+2.0	11.0	30	42.9+1.1	6.3
Weight (pounds)	1,487	170	-	30	184 8.5	46.0	29	174 6.0	32.3	30	183 5.3	29.1
Height	1,487	68.5	-	30	70.1 0.7	3.8	29	67.9 0.4	2.1	30	68.1 0.6	3.0
Sitting height, erect	1,487	35.9	-	30	36.7 0.3	1.7	29	35.6 0.3	1.3	30	36.0 0.2	1.3
Knee height	1,487	21.4	-	30	21.9 0.3	1.6	29	21.2 0.2	0.9	28	21.2 0.2	1.3
Shoulder-elbow length	-	-	-	30	14.1 0.2	1.0	28	14.5 0.1	0.5	30	14.6 0.1	0.7
Buttock-knee length	1,487	23.3	-	30	24.1 0.3	1.6	29	23.5 0.2	0.9	28	23.8 0.3	1.3
Seat breadth	1,487	14.1	-	30	15.0 0.3	1.5	29	14.7 0.2	1.3	24	15.0 0.3	1.4
Triceps skinfold (mm)	-	-	-	30	0.4 0.03	0.2	29	0.5 0.02	0.2	30	0.6 0.04	0.2
Subscapular skinfold (mm)	-	-	-	30	0.6 0.06	0.3	29	0.8 0.07	0.4	30	0.8 0.06	0.4
Endomorphy**	-	-	-	30	3.7 0.3	1.5	26	3.6 0.2	1.2	29	3.9 0.2	0.9
Mesomorphy**	-	-	-	30	4.2 0.2	1.0	26	4.5 0.2	0.8	29	4.3 0.1	0.7
Ectomorphy**	-	-	-	30	3.1 0.3	1.4	26	2.7 0.2	1.0	29	2.6 0.2	0.8

* Range
**Arbitrary Units

and the two amputee groups, and the significance of these differences are given in Table 12. There are age differences among the three groups. Though the two amputee groups do not differ significantly in age, the non-amputees are significantly ($p < .01$).

The non-amputee controls are similar in weight to the lower extremity amputees, but fully 10 pounds heavier than the upper extremity amputees. However, this difference is largely due to one control subject who weighed 370 pounds. Eliminating this subject would reduce the mean weight of the non-amputees to 177 pounds, or 3 pounds heavier than the upper extremity amputees and 6 pounds lighter than the lower extremity amputees.

Differences in height between the controls (about 2" taller) and both amputee groups are significant ($p < .01$). In erect sitting height, the controls are taller than the upper extremity group by 1.1 inches ($p < .05$), but only 0.7 inch (not significant) taller than the lower extremity group. In knee height the controls are larger by 0.7 inch in each comparison, and in buttock-knee length the controls are larger by 0.6 and 0.3 inch than the upper and lower extremity amputees. None of these differences are statistically significant, however. The direction of difference is reversed for shoulder-elbow length where the controls are smaller by 0.4 (not significant) and 0.5 ($p < .05$) inch, respectively than the upper and lower extremity groups. In seat breadth the non-amputees are broader than the upper extremity group by 0.3 inch (not significant) and are exactly the same as the lower extremity group.

Skinfolds, a measure of subcutaneous body fat, exhibit consistently lower values in the non-amputees. At the triceps they are less than the upper and lower extremity amputees by 1 and 3 mm respectively (not significant). At the subscapular region, however, the comparable figures are 5 and 6 mm (significant at $p < .05$ and $p < .01$ respectively). In the constitutional, or somatotype, ratings there were no significant differences between the controls and the two amputee groups. In endomorphy ("fat"), controls are higher by 0.1 unit than the upper extremity group, but lower by 0.2 than the lower extremity group. In the mesomorphy ("muscle") the amputees, upper and lower, are higher by 0.3 and 0.1 units. In ectomorphy ("linearity") the controls are higher by 0.4 and 0.5 units respectively.

In summary, the 30 non-amputee control subjects differ most markedly from the two amputee groups in age and most of the anthropometric differences noted are age-related. For example, the non-amputees are considerably younger and therefore would be expected to be taller (which they are), have larger body lengths and heights (which generally they do), and to have less fat (which they do). If the three groups being compared here were standardized for age, it is likely that some, though not all, of the anthropometric differences noted would be removed. The controls, compared with amputees, are younger, taller, fairly similar in weight, less fatty, and have a group tendency toward greater linearity in body build. It has been shown that much greater anthropometric differences have little or no

Table 12

Significance of Anthropometric Differences Between 30 Non-Amputee Controls, 29 Upper Extremity Amputees, and 30 Lower Extremity Amputees

Variable	Controls* vs:			
	Upper Extremity Amputees		Lower Extremity Amputees	
	Diff.	Signif.	Diff.	Signif.
Age (years)	-11.8	<.01	-15.2	<.01
Weight (pounds)	+10	n. s.	+1	n. s.
Height (inches)	+2.2	<.01	+2.0	<.01
Sitting height (inches)	+1.1	<.05	+0.7	n. s.
Knee height (inches)	+0.7	n. s.	+0.7	n. s.
Shoulder-elbow length (inches)	-0.4	n. s.	-0.5	<.05
Buttock-knee length (inches)	+0.6	n. s.	+0.3	n. s.
Seat breadth (inches)	+0.3	n. s.	0	n. s.
Triceps skinfold (mm)	-1	n. s.	-3	<.05
Subscapular skinfold (mm)	-5	<.05	-6	<.01
Endomorphy	+0.1	n. s.	-0.2	n. s.
Mesomorphy	-0.3	n. s.	-0.1	n. s.
Ectomorphy	+0.4	n. s.	+0.5	n. s.

*plus values indicate controls larger

influence on performance on the vehicle simulator (Duggar, 1963). The three groups, in other words, are physically comparable, except for age-related differences.

When the two amputee groups are compared to the general U. S. civilian population in the same age range (Table 11) the amputees are heavier, especially the lower extremity group (13 pounds), a little shorter, 0.4-0.6 inches respectively for the upper and lower extremity groups), fairly similar in the other heights and lengths available for comparison, though broader in seat breadth - a weight-related measurement. Though these comparisons are not directly relevant to the findings of the present study, it is nevertheless of interest to note how the present amputees differ from the general population.

Considerably more detailed comparisons can be made of anthropometric and morphological differences between the lower and upper extremity amputee groups in the present study. Of the 81 variables, including age, that are available for comparison (see Table 10), no differences were found that were significant at the $p < .01$ level. And at the $p < .05$ level, only the chest circumferences at rest, at maximum inspiration, and at maximum expiration, and left calf circumference (probably a random variation for only 5 measurements were available in the lower extremity group) were significantly different. The consistently larger chest circumferences of the lower extremity amputees are interesting. In view of the virtual absence of significant differences in any other body dimensions, speculations on the association between lower extremity amputation and increased chest size could center on possible increases in chest musculature or respiratory demands resulting from the extra effort of walking with a prosthesis. However, with the small numbers of individuals involved and the levels of statistical significance involved ($p < .05$), such speculations must remain to be corroborated or rejected by additional data.

Reducing the acceptance level to $p < .10$ adds only three measurements to the "significant" list, i.e., shoulder circumference (closely related to the chest measurements), left thigh circumference and right ankle circumference. Thus even at this level, only 7 of 81 measurements attain statistical significance, about the number of differences to be expected on the basis of chance alone.

A few interesting observations may be made considering gross differences in body size alone, although they are not statistically significant. The lower extremity group is 0.2 inch taller and 9 pounds heavier than the upper extremity group; this difference would probably be greater if corrections could be made for differences due to weights of the missing extremities. The lower extremity group is also found to have a somewhat larger abdomen circumference and depth and slightly larger skinfolds (a measure of fat). The greatest difference in somatotype components between the two groups is in endomorphy (roughly equitable with fatness) where the lower extremity group is again higher. Although these differences are not statistically significant, a distinct overall suggestion of greater "fatness" of the lower extremity amputees - very likely from decreased mobility and less physical activity - does emerge.

In terms of the existing anthropometric data for this study the two populations differ little, with the exception of the significantly larger chests and tendency to greater fatness of the lower extremity amputees. For most practical purposes and in the interpretation of the performance data from the vehicle simulator, the lower and upper extremity amputees used in this study can be considered anthropometrically and morphologically (with the exception of their amputations) similar.

D. Experimental Procedures

1. Task Conditions

In the experimental situation, each subject performed under a variety of steering wheel dynamics while tracking the "easy" and the "hard" target course. Variable steering wheel dynamics were: 1) wheel sensitivity, set at gains of 2, 6, or 16; and 2) wheel load set at either "no added load", "spring centering" (1 ft. lb. torque for each 5 volts fed to the integrator), "damping" (1 ft. lb. torque for each 9 volts per second change in voltage fed to the integrator, or "fixed inertia" (4 lb. in. sec.^{2}) added to the residual of the wheel and shaft (0.96 lb. in. sec.^{2}).

The three groups (non-commercial, non-amputee - commercial non-amputee and amputees) of 20 drivers who each received the full schedule experienced all 24 combinations of target and wheel conditions during each of their tracking sessions. The additional 40 partial schedule subjects experienced only 9 combinations during their single tracking session (see section E).

Order of presentation of task conditions was randomized for the first session and presented in reverse order for the second session. Task conditions could be changed without interrupting the tracking, except when changing to or from the lowest wheel sensitivity. To accomplish this, the subject had to center the wheel and wait approximately one minute for the experimenter to change the potentiometer gear. After completing the test series, the partial schedule subjects participated in a series of timed measurements of clutch and brake pedal operation.

2. Handling of Subjects

The purposes of the experiment were described to each prospective subject at the time of the first contact. The nature of the task and personal data to be collected were explained and an appointment made at the convenience of the subject for the interviews and first session. For some of the amputees, the interview was scheduled several days before the first session due to the amount of time required to conduct the clinical interview.

When a subject arrived for his first session he completed a questionnaire (see Appendix A). If an amputee, the subject might have completed the first part of the clinical interview. If the amputee had not, the interview was given at that time. Other subjects proceeded directly to the tracking task. The anthropometric measurements sessions were conducted at opportune times rather than in fixed sequence to the other sessions.

The procedures for the tracking task for all subjects receiving the full schedule (24 test conditions at each of two sessions) were as follows:

1) The subject was shown the tracking apparatus, and the task - maintaining the line and dot in coincidence - was explained.

2) Seating and display brightness were adjusted to be comfortable for the subject.

3) The subject was given an easy tracking task for practice.

4) After the subject had practiced for a few minutes, the wheel sensitivity was varied over the range available with the gear ratio.

5) Sensitivity was readjusted to an intermediate value and the subject allowed to experience each of the control loads.

6) The target spectrum was switched to "hard", and the operator practiced for the remainder of a total of ten minutes.

7) The subject was required to center the wheel by visually monitoring the scope bringing the line to a complete stop after tracking practice. Accuracy of centering was checked with a voltmeter on the input to the integrator and was required to be within one-tenth of a volt (representing a drift rate of less than 0.02 inches per second at a sensitivity setting of 4). Ability to meet this criterion was used to screen for gross visual defects that might interfere with tracking performance.

8) The subject was then given a five minute rest, during which time he was reminded of the need to do his best at all times so that the data would be representative of his actual abilities.

9) The seat and display brightness were then readjusted if the subject so desired, and the first test was begun.

10) After two tests the subject was given a five minute rest followed by series of three tests separated by five minutes rest periods.

When the subject returned for his second tracking session, a similar procedure was followed except the initial practice period was only three minutes long with a two minute break.

The abbreviated or partial schedule given to 40 of the amputees was administered in an identical manner, only nine tests were given in a single session. After completing the tracking tests, 36 of the amputees and 7 members of the laboratory staff were asked to practice using the brake and clutch pedal. Subjects were instructed to rest their right foot against the accelerator and the left foot against the firewall to the left of the clutch. On command the subject moved his foot from the accelerator to the brake or from the firewall to the clutch and fully depressed the pedal. After these motions had each been practiced several times a series of ten timed trials were recorded for each movement. For each trial the subject was advised as to the expected move and that the foreperiod before the signal would be less than 10 seconds.

E. Data Collection

Error scores and real and imaginary components of the describing functions were measured by hand from the records of the last minute of each test. The measured trace deflections and calibration data for each session were transferred to punch cards. These data were then processed on a digital computer to provide system response (closed-loop) amplitude ratios and phase angles at each frequency. The amount of error predicted from the describing functions was computed for each test and compared with the observed error.

Limitations on data accuracy are due to time variation in the performance characteristics of the subjects, small amounts of drift in D. C. amplifier circuits, and constraints on the resolution of the chart records. Based on a series of pilot studies on highly trained subjects, it is estimated that reported integrated error scores are within ± 1 volt minutes. Since observed error scores range from 6 to 40 volt minutes, depending upon task variables and subject's skill, the uncertainty varies from 2.5 to 16 per cent with the greatest proportionate uncertainty occurring during tests with the best performance. Real and imaginary components of the describing functions for various frequencies can be resolved to ± 0.1 units out of a total of from 1.5 to 30 units. This uncertainty represents a greater proportion of the total output with the larger control gains and smaller amplitude ratios. Thus, with a control gain of 16 the phase error could have been as much as 4 degrees.

VII. RESULTS OF THE EXPERIMENTAL PROGRAMS

A. Tracking - Full Schedule

1. Error Scores

A five-way analysis of variance (ANOVA) was performed for the integrated error, computed error (that predicted from the describing function data) and remnant error (integrated error minus computed error). Due to computer program restrictions it was possible to compute only major effects and simple interactions. However, hand-computed analyses of pilot study results indicated no important three-way interactions among task variables.

The ANOVA for integrated error appears in Table 13. All main effects were statistically significant at the .001 level or better when tested against the residual mean square. However, statistically significant interactions between spectrum and each of the other variables suggest that the main effects may be important only with the difficult spectrum. No other interactions were statistically significant. Cell means are listed in Table 14 and plotted in Figures 22, 23, 24 and 25. Figures 22 and 23 show that with the easy spectrum (spectrum I), session and load had little influence on error, but with the difficult spectrum more substantial differences in average error were observed between sessions. Figure 24 shows that gain effects also varied with spectrum and that session effects did not interact with gain. Figure 25 shows that group differences were in the same direction for both spectrums and all gains, but greater differences were observed with the difficult spectrum. Group 1 produced more error than did group 3 (amputees) who produced more error than did group 2 (truck drivers) for all conditions.

Average integrated error scores for each group were compared using the Newman-Keuls sequential range test (Duncan, 1955). The mean scores for each group of subjects averaged over all conditions and sessions all differed one from another by statistically significant amounts. That is, the control group error was greater than the truck driver group ($p < 0.01$) and the amputee group ($p < 0.05$), while the amputee group error was also significantly greater than the truck driver group error ($p < 0.05$). When the group averages for each spectrum were compared sequentially only the difference between the control and truck driver groups were significant ($p < 0.01$) with spectrum II. However, all group scores with spectrum II were greater than any of the group scores with spectrum I ($p < 0.01$).

Average integrated error scores for each gain setting with each spectrum were also compared using the Newman-Keuls test. For both spectrums the error with a gain of 2 was significantly greater than with a gain of 6 or 16 ($p < 0.01$ with spectrum II, $p < 0.05$ with spectrum I). Error scores for gains of 6 and 16 did not differ by a statistically significant amount ($p < 0.05$).

The statistical tests confirm that: 1) task variables, gain and spectrum, affect tracking error; 2) differences between groups are not significant for the easy task; and 3) professional drivers perform with less error with the difficult spectrum than did the controls; 4) the amputee group performance does not differ significantly from that of either the professional drivers or the controls.

Table 13

Analysis of Variance
Integrated Error Scores
(F Ratios Listed Use the Residual Mean Square as the Denominator)

Effect	Sum of Squares	Degrees of Freedom	Mean Square	F
Session (T)	6233.30	1	6233.30	42.3*
Spectrum (S)	336455.56	1	336455.56	2280.9*
Group (A)	21432.57	2	10716.29	72.6*
Gain (G)	51473.70	2	25736.95	174.5*
Load (L)	9943.22	3	3314.41	22.5*
T x S	1876.29	1	1876.29	12.7*
T x A	708.64	2	354.32	2.4
T x G	42.88	2	21.44	0.1
T x L	15.62	3	5.21	0.0
S x A	1253.12	2	626.56	4.2***
S x G	3001.70	2	1500.85	10.2*
S x L	2160.50	3	720.17	4.9**
A x G	558.58	4	139.64	0.9
A X L	1713.20	6	285.53	1.9
G x L	521.78	6	86.96	0.6
T x S x A x G x L	423.91	12	35.33	0.2
Residual	417012.88	2827	147.51	
Total	854827.66	2879		

*$p < .001$ (All main effects not significant when tested against their interaction with spectrum, spectrum significant at the 0.05 level when tested against its largest interaction).

**$p < .01$

***$p < .05$

Table 14

Mean Integrated Error Scores

		All Loads	Springs	Damping	Inertia	No Load
	Session 1	12.41	12.05	11.73	13.15	12.73
Spectrum I	Session 2	11.95	11.92	11.22	12.48	12.18
	Session 1	20.76	19.55	20.38	21.78	21.43
Spectrum II	Session 2	19.05	17.45	18.77	20.27	19.75

		Gain			
		2	6	16	All Gains
	Session 1	14.04	11.83	11.35	12.41
Spectrum I	Session 2	13.56	11.43	10.85	11.98
	Session 1	23.25	20.45	18.64	20.77
Spectrum II	Session 2	21.66	18.50	17.23	19.14
	Control Group	14.55	12.49	12.03	13.02
Spectrum I	Truck Drivers	13.08	10.60	9.91	11.20
	Amputees	13.80	11.81	11.36	12.32
	Control Group	24.25	21.26	18.64	21.48
Spectrum II	Truck Drivers	20.96	17.94	16.59	18.48
	Amputees	22.20	19.25	18.35	19.93

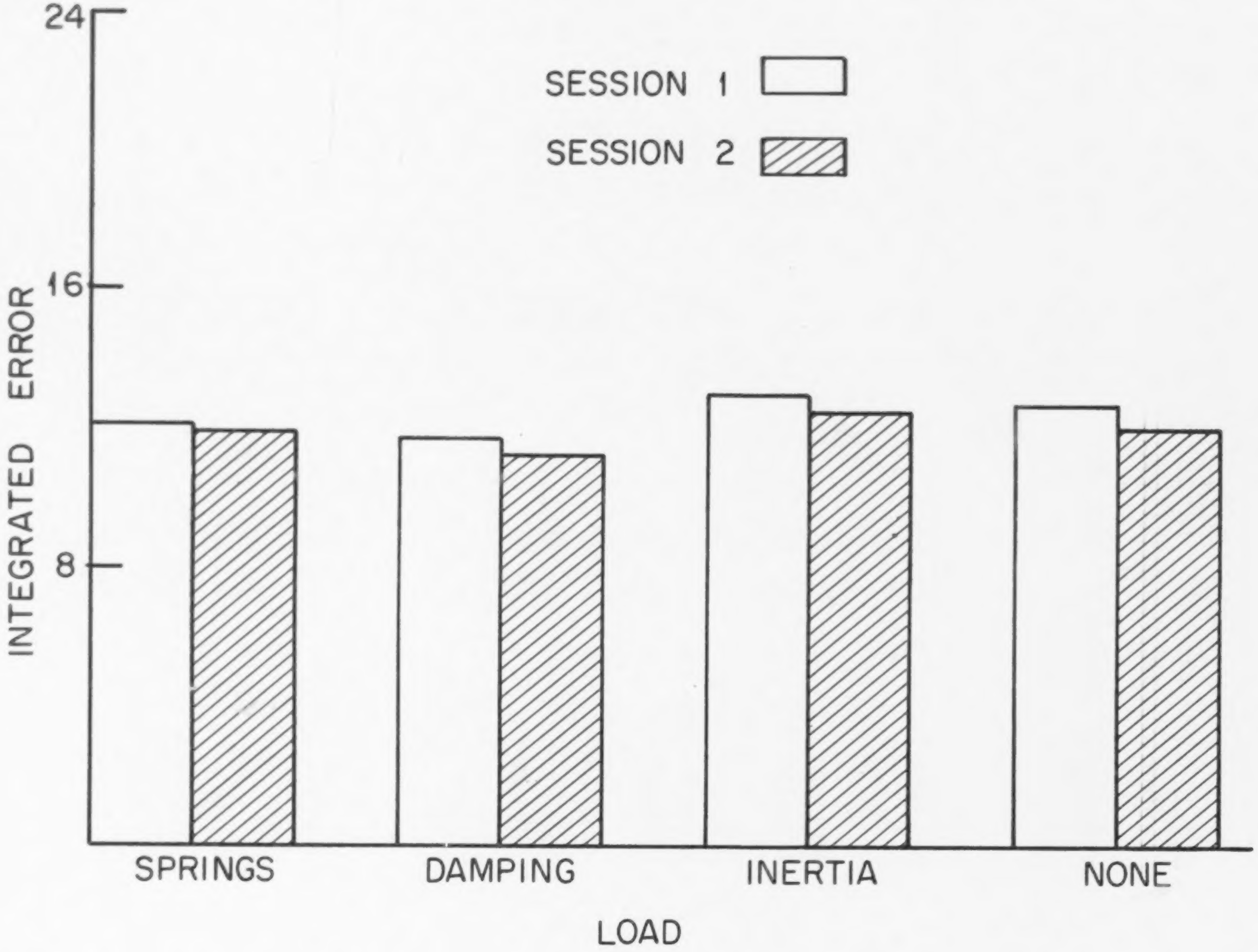


FIG. 22. SPECTRUM 1 INTEGRATED ERROR AVERAGED FOR ALL GAINS AND GROUPS PLOTTED AS A FUNCTION OF LOAD

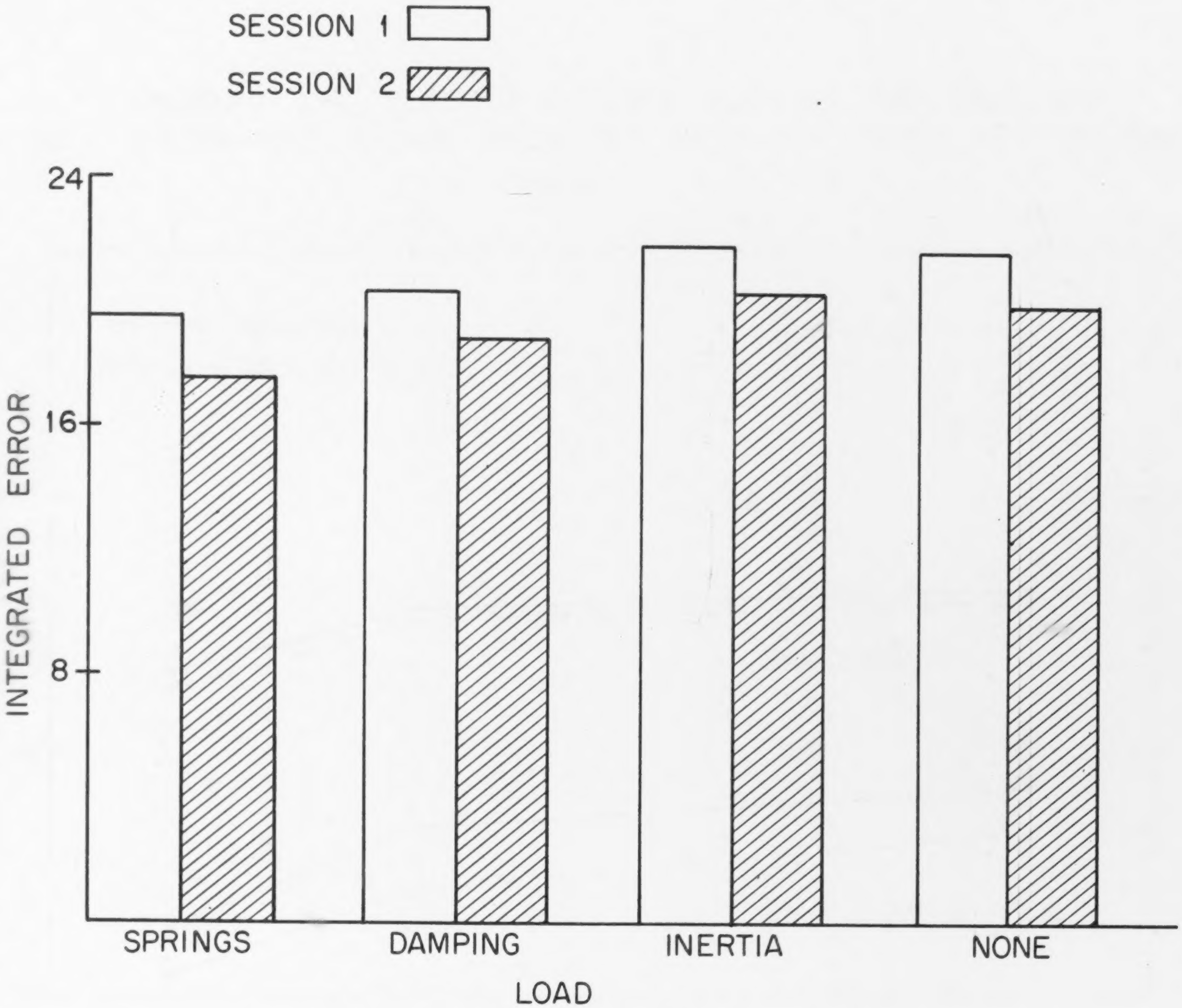


FIG. 23. SPECTRUM 2 INTEGRATED ERROR AVERAGED FOR ALL GAINS AND GROUPS PLOTTED AS A FUNCTION OF LOAD

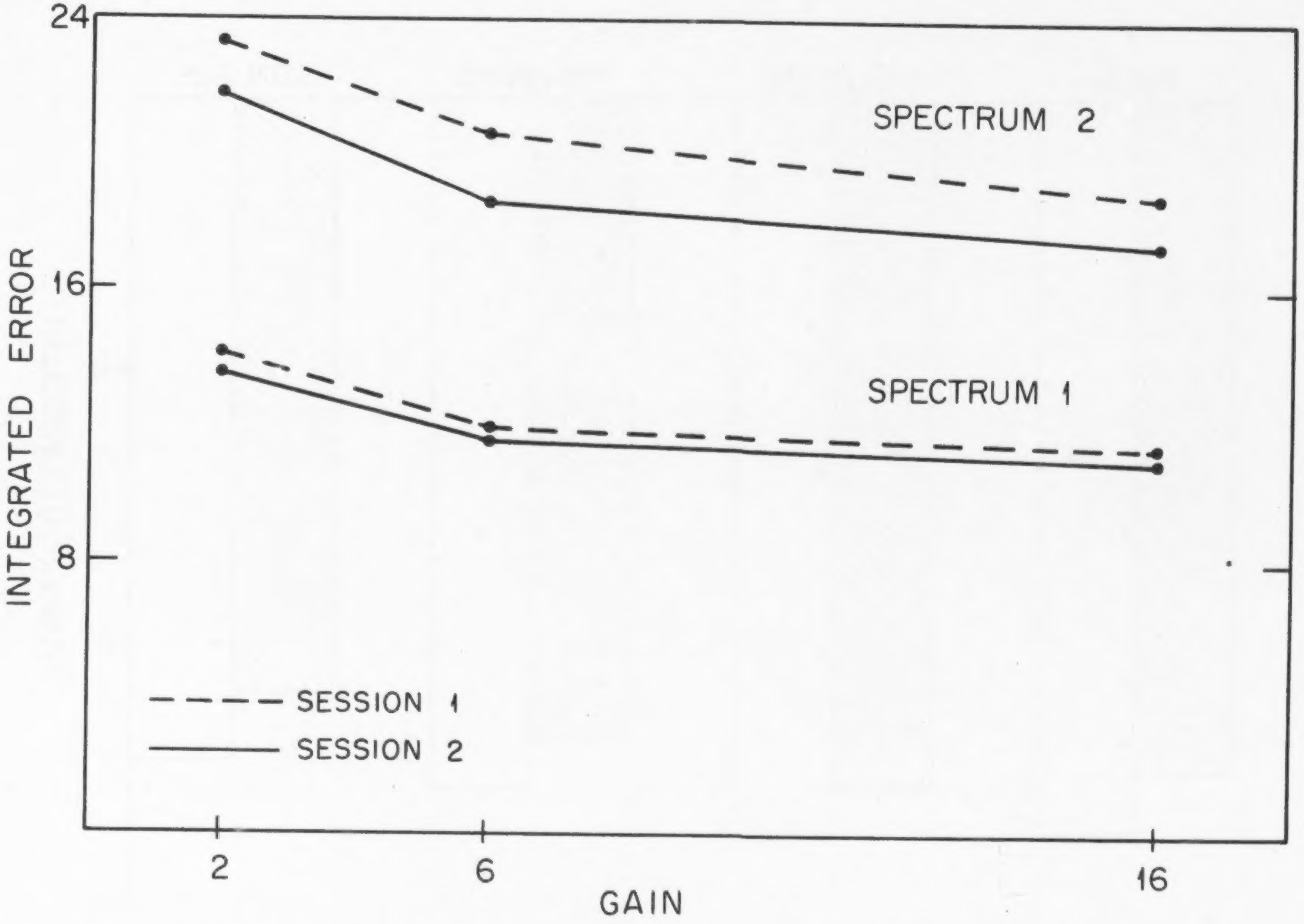


FIG. 24. INTEGRATED ERROR AVERAGED OVER ALL LOADS AND GROUPS SHOWING THE EFFECTS OF GAIN, SESSION AND SPECTRUM.

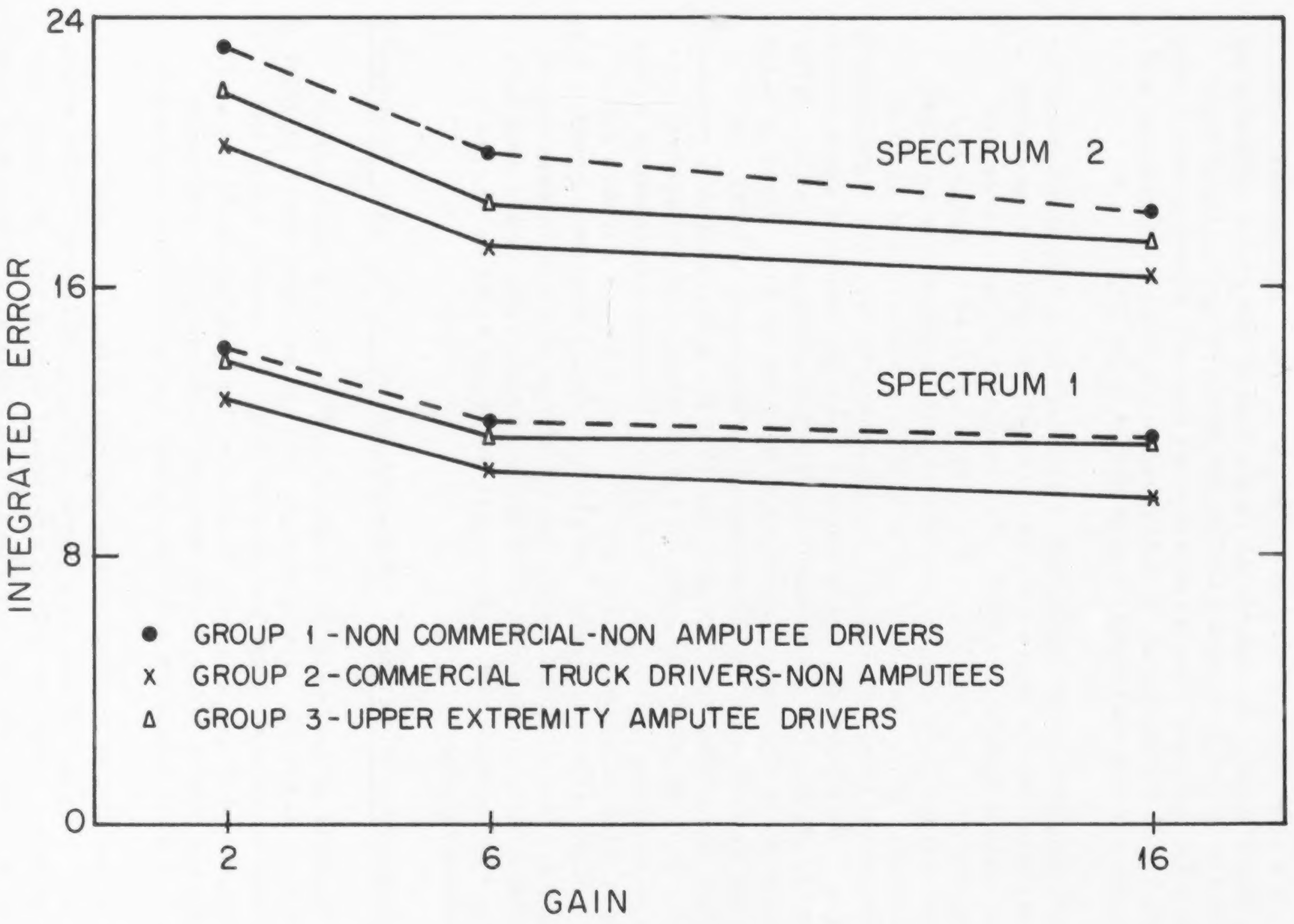


FIG. 25. INTEGRATED ERROR AVERAGED OVER ALL LOADS PLOTTED FOR EACH GROUP AS A FUNCTION OF GAIN. ONLY SECOND SESSION DATA WERE USED.

Average error scores computed from the describing function data system error appear in Figure 26. An ANOVA of these data is listed in Table 15. Again all main effects are significant when tested against the residual, but only spectrum and group effects remain significant when tested against their largest interaction mean square. Of particular interest is the fact that group interactions with gain, load, and session are statistically significant. A sequential range test of the group differences indicates that the error accounted for by the describing functions was less ($p < 0.01$) for group 2 (the truck drivers) than for either group 3 (the amputees) or group 1 (controls), but differences between the control and amputee groups are not statistically significant ($p > 0.05$).

Subtracting the error computed with describing functions from the observed integrated error leaves a small remainder which represents error due to system non-linearities. The remnant error scores are plotted in Figure 27. An ANOVA of these data appears in Table 16. Again all main effects are significant when tested against the residual, but only spectrum, gain, and load are significant when tested against their largest interaction. Group and session effects interact significantly with spectrum. With the easy spectrum the average remnant approaches the limits of resolution for the method and is therefore unreliable. With the difficult spectrum the average remnant is three or four times greater and is believed to provide a useful measure of nonlinear effects. A Newman-Keuls sequential test determines that the differences in remnant error for spectrum II averaged over all loads, gains, and sessions are statistically significant ($p < 0.01$). The group 1 (controls) remnant error is significantly greater than that for groups 2 or 3 (truck drivers and amputees), and the remnant error for group 2 is significantly greater than that for group 3. Examination of Figure 27 shows that the interaction of group and gain effects produces a reversal in group rank order only at a gain of 2 with spectrum II although magnitude of gain effects varies markedly between groups.

2. Describing Functions: Objective Scores of Operator Responses

Results of analyses of variance of the describing function data are listed in Table 17. Main effects, except session, were statistically significant when tested against the residual for nearly all of the amplitude ratios and phase angles. However, the generality of the statistically significant interactions occurred with each measure and many main effects for each measure must therefore be interpreted cautiously.

Examples of the describing function data are plotted in Figures 28-35. Effects of load are shown in Figures 28 and 29 for representative conditions. Effects of load are small during both sessions and with either spectrums. Differences between groups as a function of load are only noted for the phase lag at the highest frequency with either spectrum and for the amplitude ratio at this frequency with the easy spectrum. Figures 30 and 31 illustrate the effects of gain on describing function data for group 1 (control group). As wheel sensitivity increases, phase lag

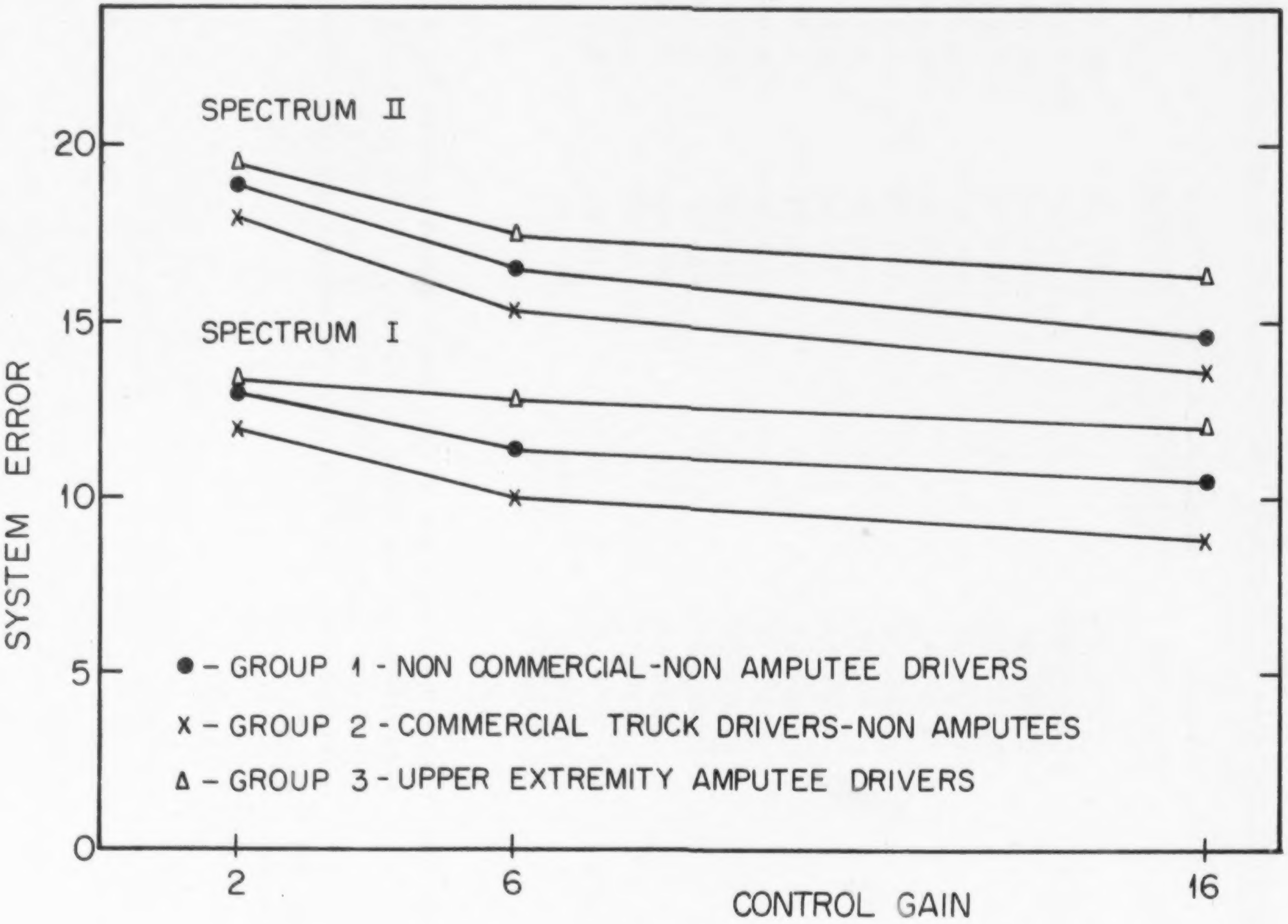


FIG. 26 SYSTEM ERROR AVERAGED OVER ALL LOADS AND SUBJECTS WITHIN EACH GROUP, SECOND SESSION ONLY.

Table 15

Analysis of Variance
Computed Error Scores
(F Ratios Listed Use the Residual Mean Square as the Denominator)

Effect	Sum of Squares	Degrees of Freedom	Mean Square	F
Session (T)	2598.67	1	2598.67	22.2*
Spectrum (S)	236633.89	1	236633.89	2019.8*
Group (A)	27696.98	2	13848.49	118.2*
Gain (G)	46917.88	2	23458.94	200.2*
Load (L)	4024.94	3	1341.65	11.5*
T x S	1188.96	1	1188.96	10.1**
T x A	720.01	2	360.00	3.1***
T x G	12.72	2	6.36	0.1
T x L	83.52	3	27.34	0.2
S x A	396.54	2	198.27	1.7
S x G	4417.97	2	2208.99	18.9*
S x L	1562.57	3	520.86	4.4**
A x G	2584.47	4	646.12	5.5*
A x L	1508.64	6	251.44	2.1***
G x L	329.33	6	54.87	0.5
T x S x A x G x L	373.64	12	31.14	0.8
Residual	331203.98	2827	117.16	
Total	662254.70	2879		

* $p < 0.001$ (when the five main effects were tested against their significant interactions' mean squares the spectrum effect was significant at the 0.01 level, the group effect at the 0.05 level, and all others non-significant).

** $p < 0.01$

*** $p < 0.05$

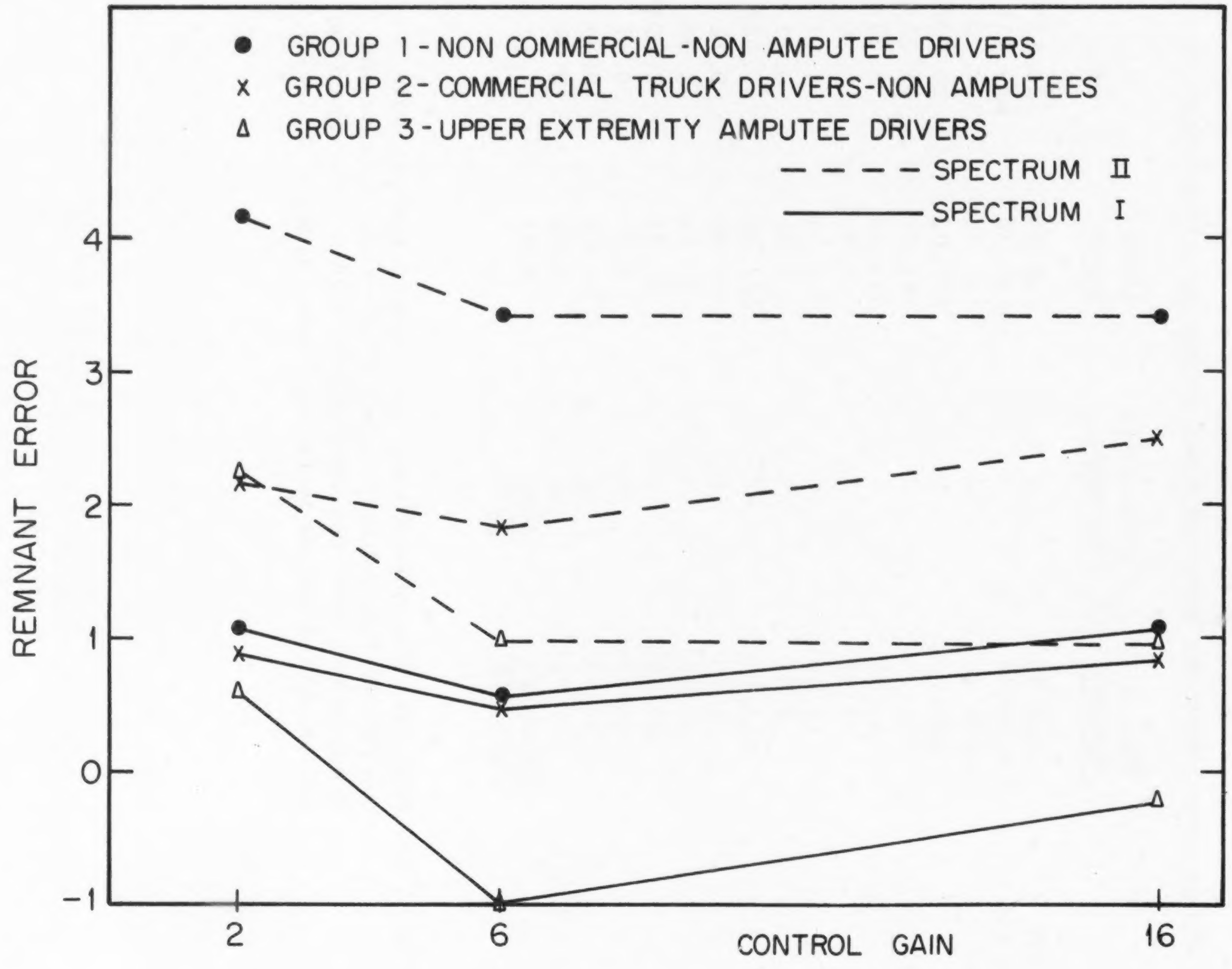


FIG. 27. REMNANT ERROR AVERAGED OVER ALL LOADS AND SUBJECTS WITHIN EACH GROUP, SECOND SESSION ONLY.

Table 16

Analysis of Variance
Remnant Error Scores
(F Ratios Listed Have the Residual Mean Square as a Denominator)

Effect	Sum of Squares	Degrees of Freedom	Mean Square	F
Session (T)	218.95	1	218.95	29.53*
Spectrum (S)	4657.30	1	4657.30	628.13*
Group (A)	2295.45	2	1147.72	154.79*
Gain (G)	386.05	2	193.02	26.03*
Load (L)	371.75	3	123.92	16.71*
T x S	33.28	1	33.28	4.49***
T x A	3.86	2	1.93	0.26
T x G	13.49	2	6.74	0.91
T x L	4.67	3	1.56	0.21
S x A	445.19	2	222.59	30.02*
S x G	1.75	2	0.88	0.12
S x L	33.38	3	11.13	1.50
A x G	85.68	4	21.42	2.89***
A x L	22.88	6	3.81	0.51
G x L	37.35	6	6.22	0.84
T x S x A x G x L	31.90	12	2.66	0.36
Residual	20960.82	2827	7.41	
Total	29603.72	2879		

* $p < 0.001$ (when the five main effects were tested against their significant interactions' mean squares the session and group effect were not statistically significant. Spectrum gain and load effects were significant at the 0.05 level).

*** $p < 0.01$

Table 17

Results of Analysis of Variance of Describing Function Data. Only Probabilities of Chance Occurrence ≤ 0.05 are Listed. F Values Used Residual Mean Squares as the Denominator. Amplitude Ratios (A_i) and Phase Lags (O_i) are for .041, .107, .229, and .530 Degrees.

Effect	Degrees of Freedom	A_1	O_1	A_2	O_2	A_3	O_3	A_4	O_4
Session (T)	1	$<.001$*	$<.01$*	$<.001$*			$<.001$*	$<.01$*	
Spectrum (S)	1	$<.001$**	$<.001$*	$<.001$**	$<.001$**	$<.001$*	$<.001$*	$<.001$**	
Group (A)	2	$<.001$**	$<.001$**	$<.001$*	$<.001$*	$<.001$*	$<.001$***	$<.001$*	$<.001$***
Gain (G)	2	$<.001$*	$<.001$**	$<.001$*	$<.001$*	$<.001$**	$<.001$**	$<.001$***	$<.001$**
Load (L)	3	$<.001$*	$<.001$***	$<.001$***	$<.001$*		$<.001$*	$<.01$*	$<.001$***
T x S	1				$<.01$		$<.001$		
T x A	2		$<.05$	$<.01$		$<.001$			
T x G	2	$<.05$							
T x L	3								
S x A	2	$<.05$		$<.05$		$<.001$		$<.001$	
S x G	2		$<.01$		$<.001$		$<.001$		$<.05$
S x L	3	$<.05$					$<.05$	$<.01$	
A x G	4	$<.001$	$<.01$		$<.001$			$<.05$	
A x L	6								$<.05$
G x L	6							$<.05$	

*** $p < .01$ when tested against the effect's largest interaction
** $p < .05$ when tested against the effect's largest interaction
* Not significant when tested against the effect's largest interaction

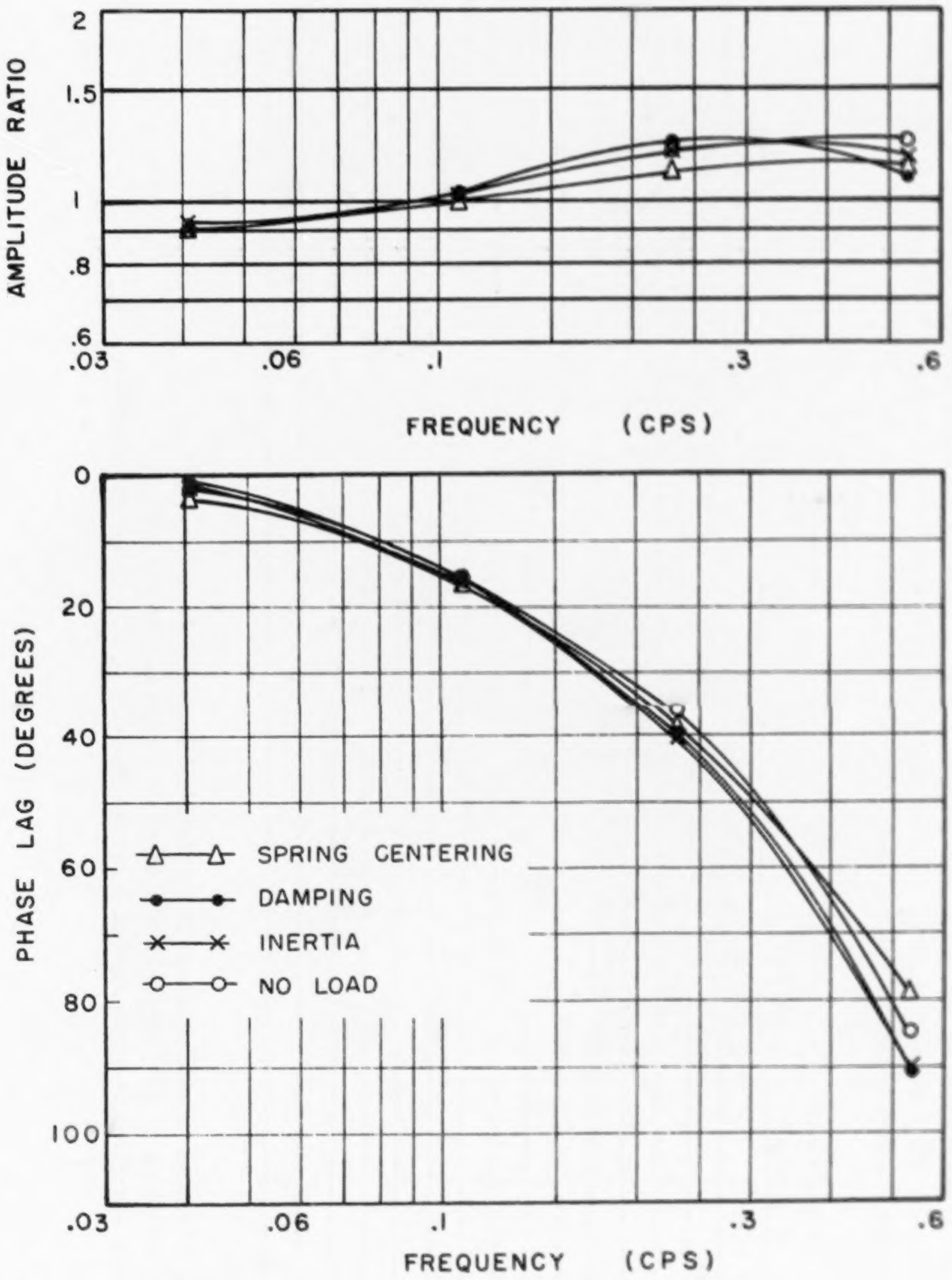


FIG. 28 EFFECTS OF LOAD, GROUP 3, SPECTRUM 1, SESSION II, GAIN 6.

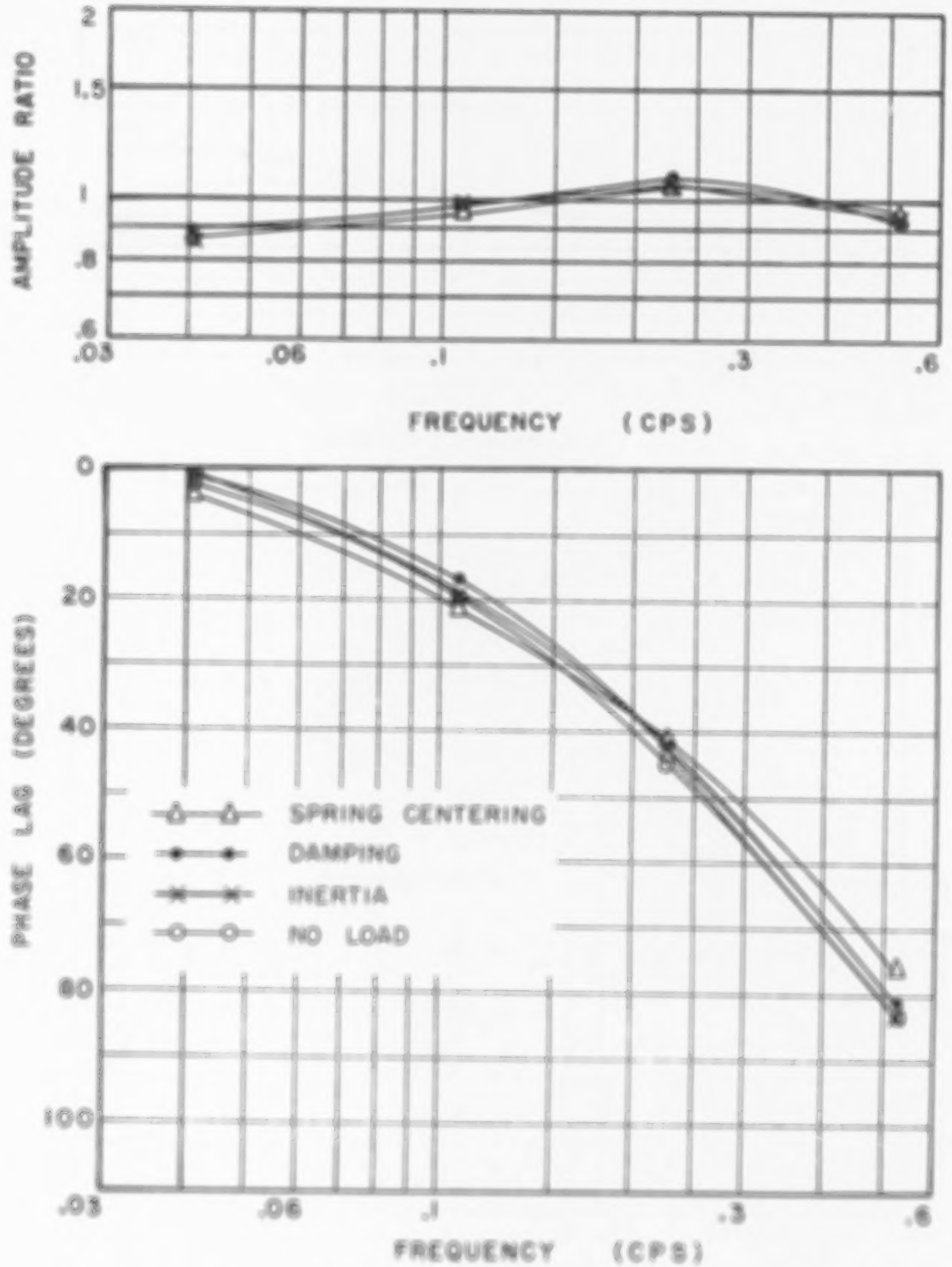


FIG. 29 EFFECTS OF LOAD, GROUP 3, SPECTRUM 2, SESSION II, GAIN 6.

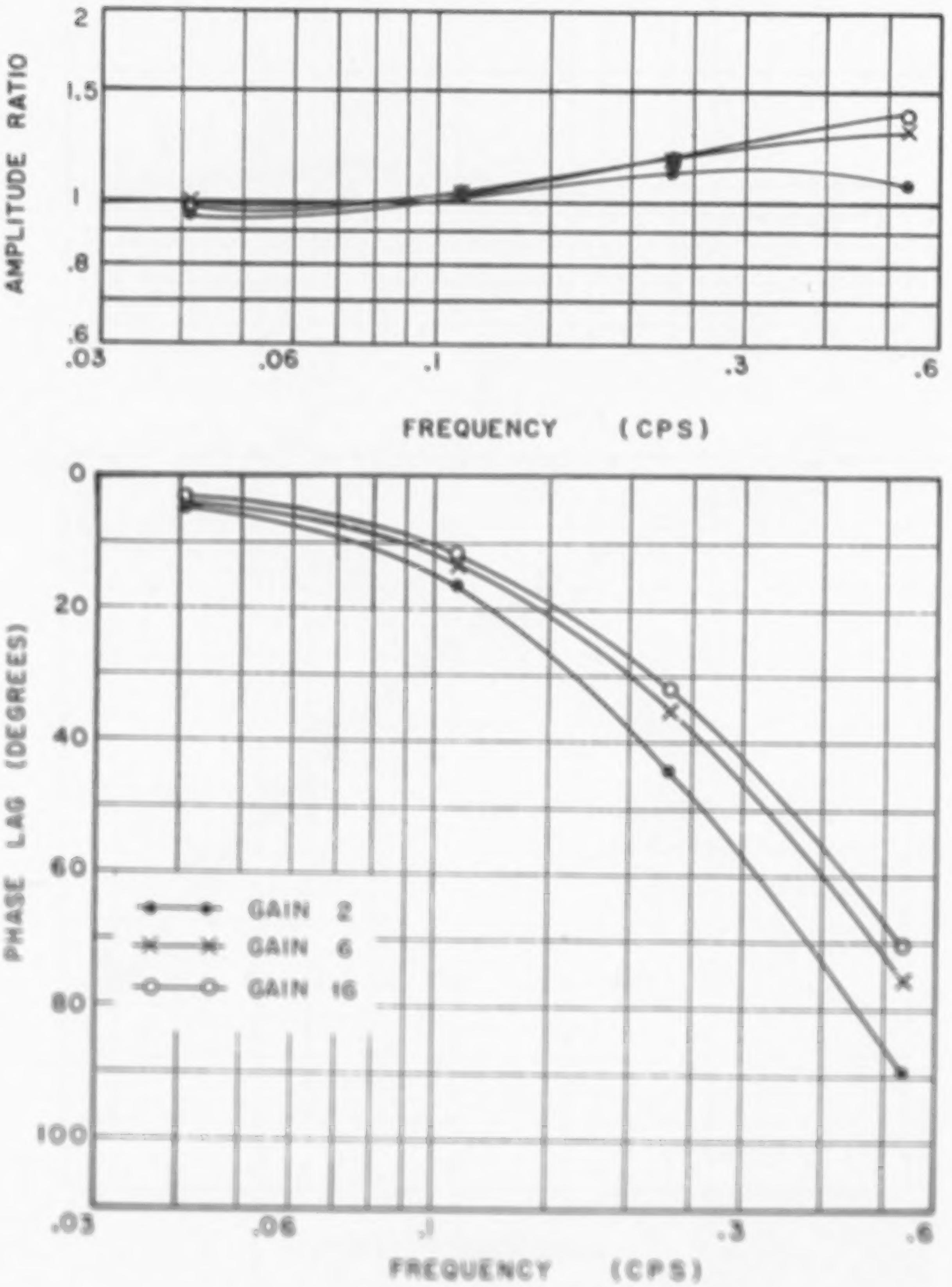


FIG. 30 EFFECTS OF GAIN, GROUP 1, SPECTRUM 1, SESSION II. AVERAGED OVER ALL LOADS FOR ALL SUBJECTS.

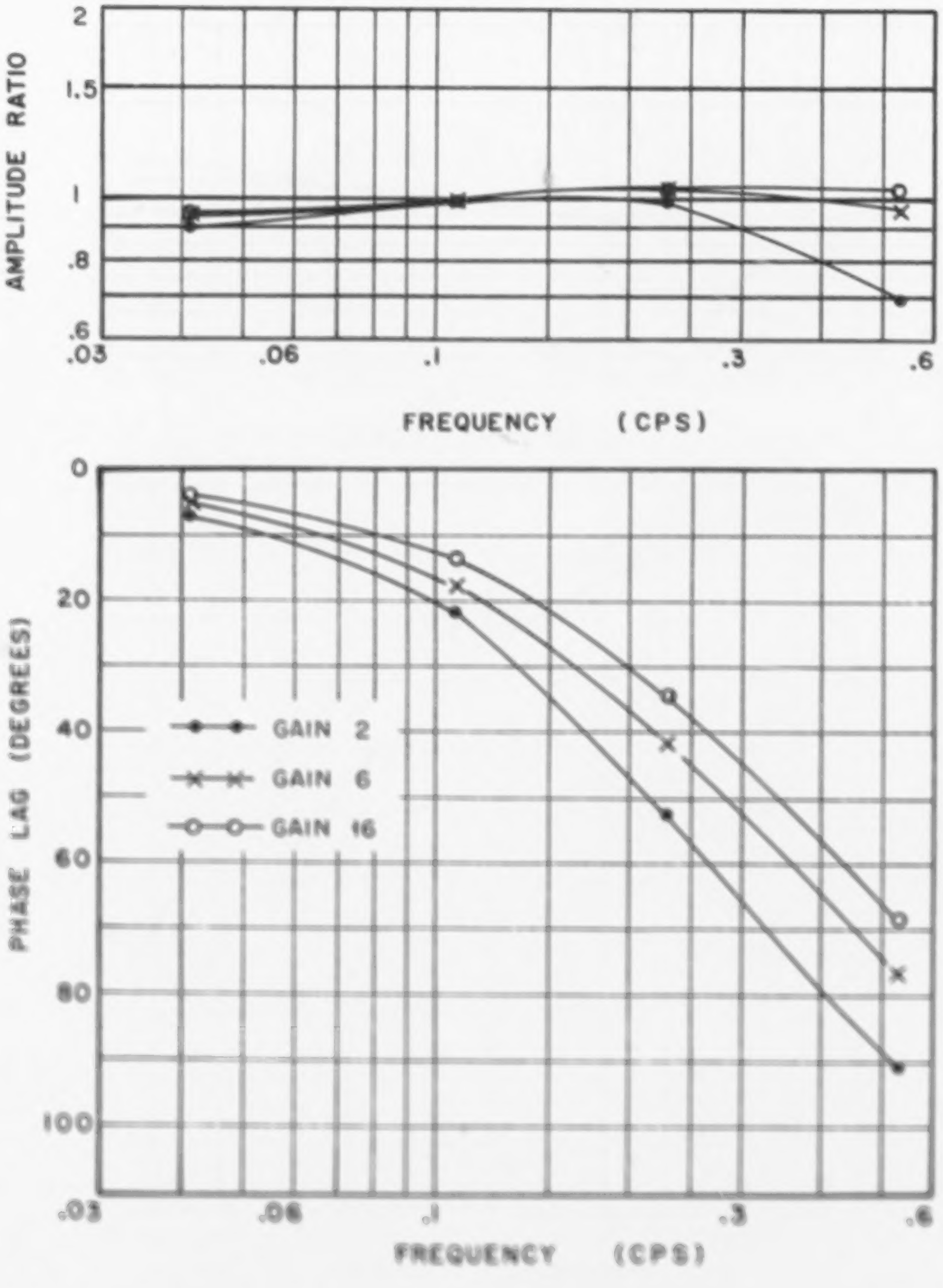


FIG. 31. EFFECTS OF GAIN, GROUP 1, SPECTRUM 2, SESSION II. AVERAGED OVER ALL LOADS FOR ALL SUBJECTS.

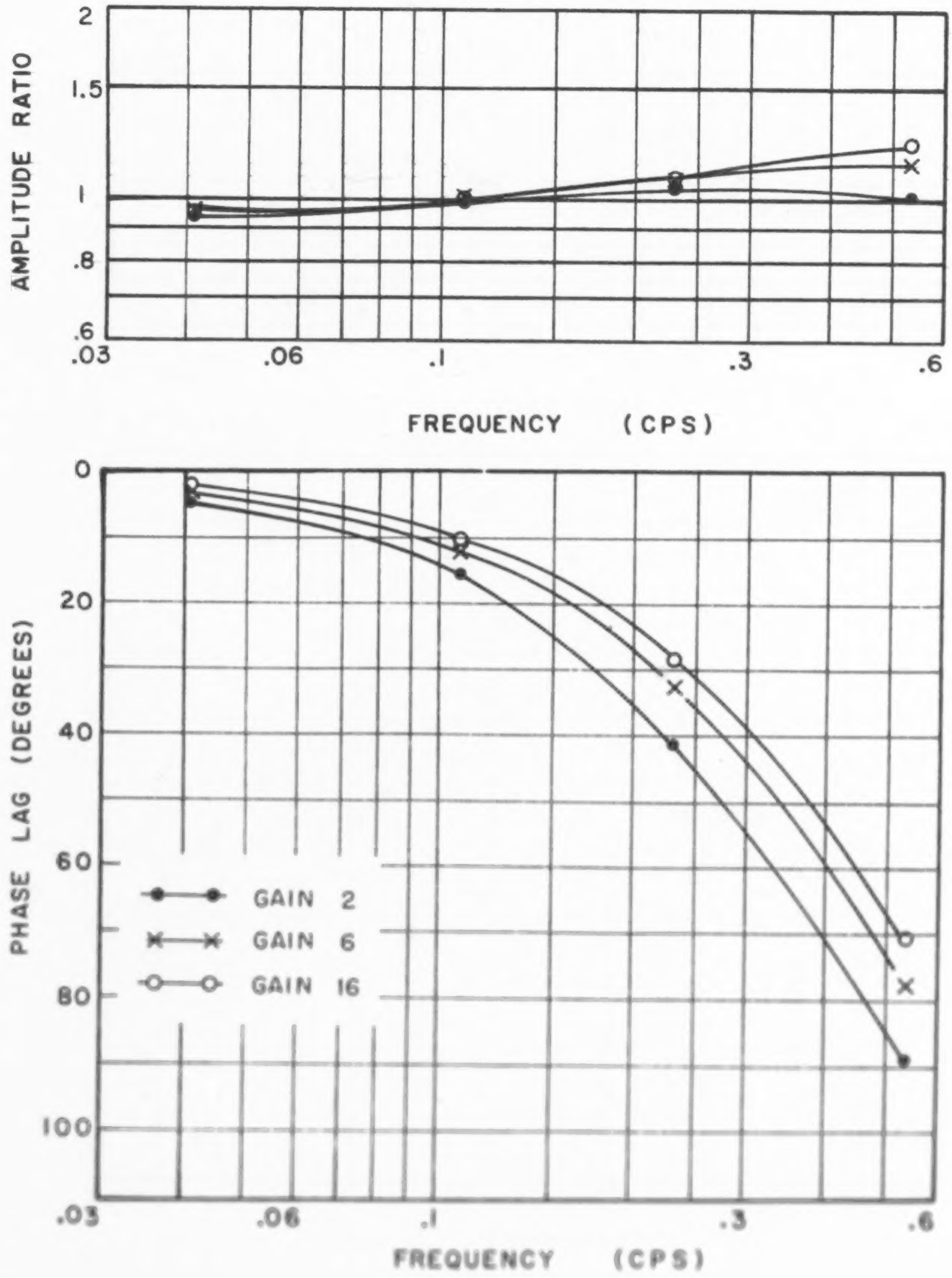


FIG.32. EFFECTS OF GAIN, GROUP 2, SPECTRUM 1, SESSION II. AVERAGED OVER ALL LOADS FOR ALL SUBJECTS.

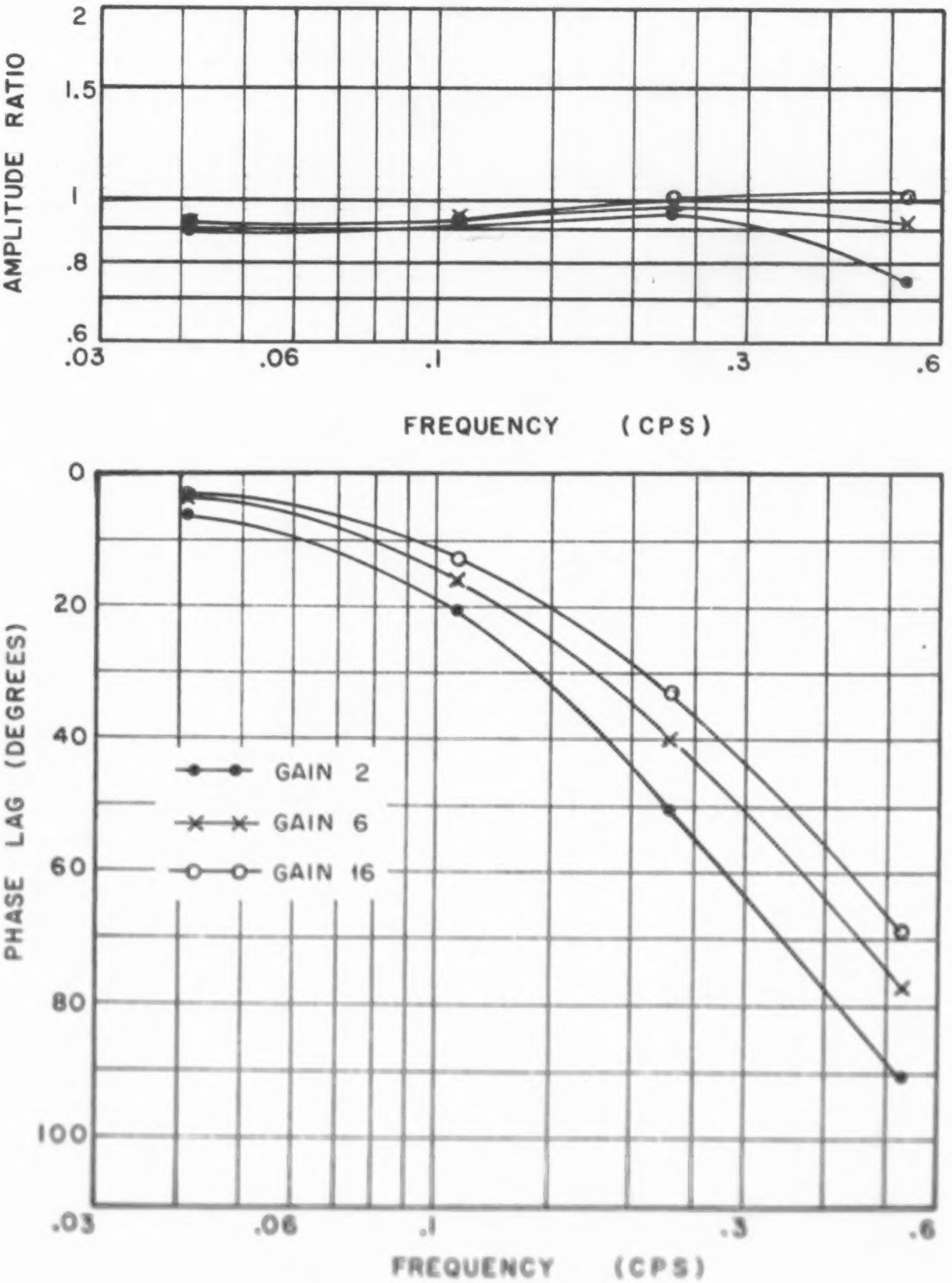


FIG. 33. EFFECTS OF GAIN, GROUP 2, SPECTRUM 2, SESSION II. AVERAGED OVER ALL LOADS FOR ALL SUBJECTS.

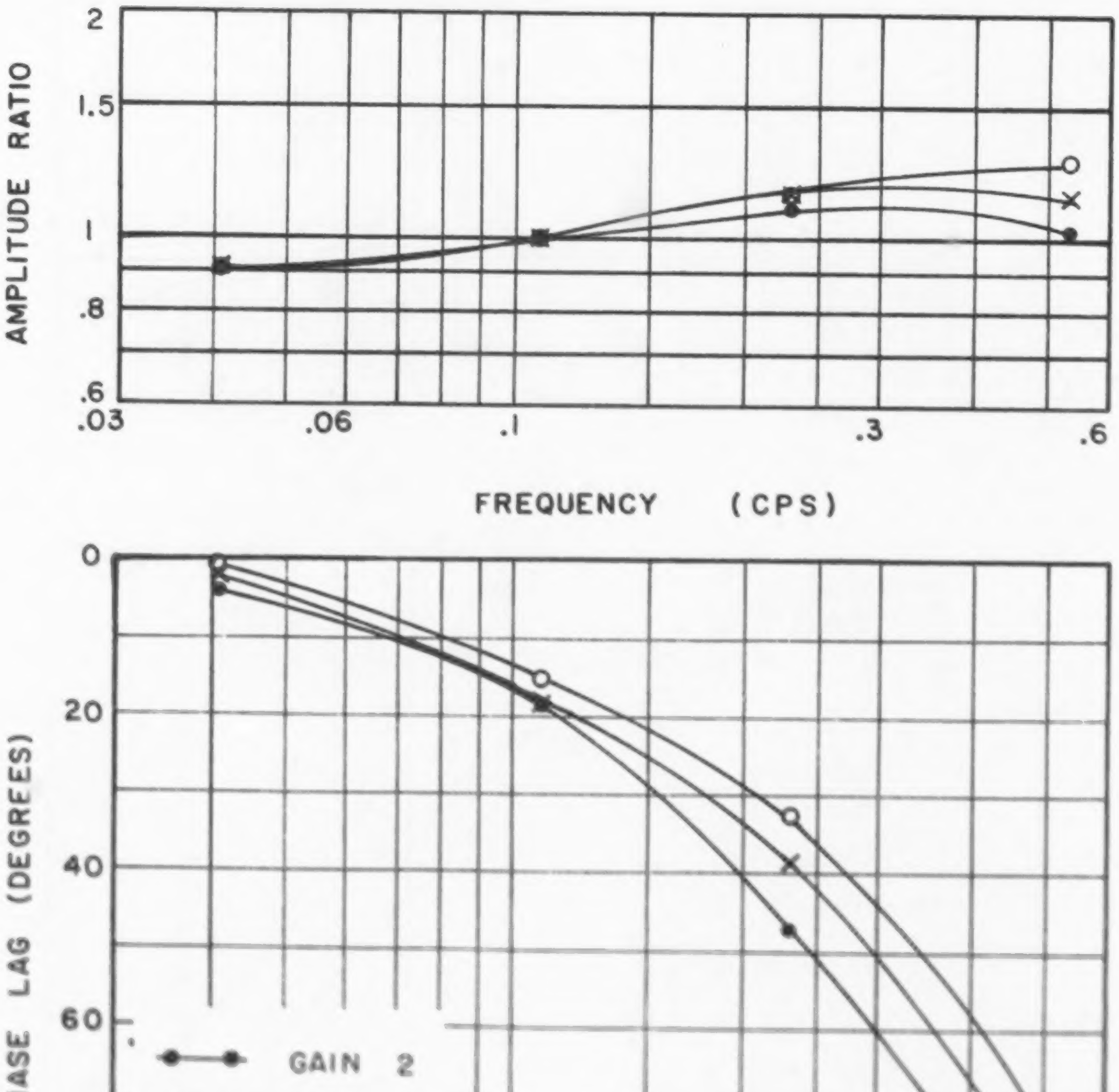


FIG. 34 EFFECTS OF GAIN, GROUP 3, SPECTRUM 1, SESSION II. AVERAGED OVER ALL LOADS FOR ALL SUBJECTS.

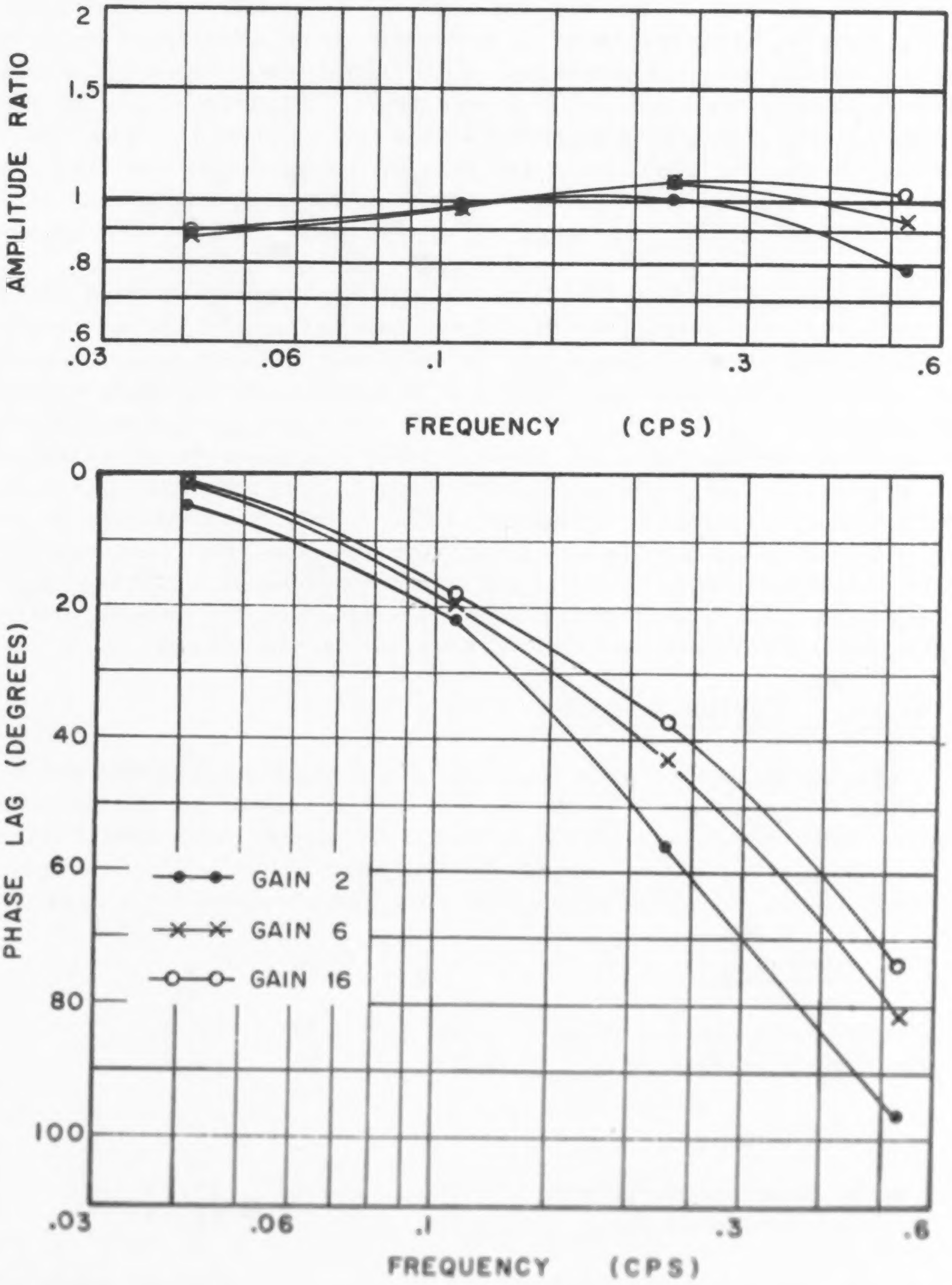


FIG. 35. EFFECTS OF GAIN, GROUP 3, SPECTRUM 2, SESSION II. AVERAGED OVER ALL LOADS FOR ALL SUBJECTS.

decreases at all frequencies. There are no differences in amplitude ratios between gains of 6 and 16, but decreasing wheel sensitivity to a gain of 2 results in large, high frequency attenuation. Attenuation at .530 cps is greatest with the hard spectrum as gain decreases. Spectrum and gain interacts significantly for phase lag at all frequencies, the effects of gain are enhanced with the more difficult spectrum. Figures 32 and 33 show the same effects with group 2 (professional truck drivers). The effects of changes in gain on attenuation are less for group 2 than for the other groups. Effects of gain for group 3 (amputees) appear in Figures 34 and 35. Results with group 3 are qualitatively similar to those with group 1.

Describing function data are markedly influenced by gain. Differences between groups are less than those between any of the gain settings and of the same order of magnitude as the maximum differences between loads. Although it is not clear that it is meaningful to compare averages of the amplitude ratios and phase lags obtained from many tests, differences between the averages are confirmed by the analysis of system error data. In general, the professional drivers perform with less phase lag and amplitude at the higher frequencies than either the amputees or control group. Although the control group has greater lower frequency lag than the amputees, their lower lag at other frequencies produces less system error. The high remnant error produced by the control group is unexplained and accounts for their greater integrated error.

B. Tracking - Partial Schedule

Average performance data for the partially scheduled subjects were computed and compared with the first session data for the full schedule subjects. No important differences have been found. Representative average integrated error score comparisons appear below. The averages for full schedule amputees are for comparable loads and the first session.

Spectrum I		Gain	
	2	6	16
Partial Schedule Amputees	13.48	11.39	10.83
Full Schedule Amputees	12.97	11.95	10.94
Spectrum II			
Partial Schedule Amputees	21.90	17.96	19.05
Full Schedule Amputees	22.45	18.61	19.97

The partial schedule includes both upper and lower extremity amputees. All full schedule amputees have upper extremity impairments.

C. Foot Control Motions

A group of 36 of the amputee subjects were tested for speed of moving the left foot from the firewall to full depression of the clutch, and the right foot from the accelerator to deflection of the brake pedal. The average from 10 trials from both legs are listed in Table 18 together with comparable data from 7 members of the laboratory staff. It is of interest to note that both the shortest and longest times for accelerator to brake motion were measured for the amputees (using an intact limb).

In the present study it was possible only to determine the time relationships in the foot control movements. Other factors of importance which require further study relate to the force levels involved in the operation of the foot pedals, and the influence of various kinds of prosthetics.

Table 18

Average Foot Movement Time, in Seconds
Two Trials - 10 Tries per Trial

A/B = Accelerator to Brake F/C = Firewall to Clutch
A/K = Above Knee Amputee - no data taken

1. Laboratory Staff

Subject	Movement	
	A/B	F/C
G. T.	.744	.738
T. C.	.513	.633
R. D.	.510	.510
S. T.	.546	.546
R. M.	.576	.585
H. S.	.501	.636
J. L.	.555	.570
Mean ± S. D.	.568 ± .073	.596 ± .070

2. Amputees

Subject	Movement	
	A/B	F/C
R. R.	.810	.990
F. F.	.603	.603
C. H.	.732	.750
A. R.	.690	AK
C. W.	.996	.690
W. F.	AK	.672
D. M.	.660	AK
N. G.	.834	.681
E. T.	.555	.645
H. L.	.690	AK
R. D.	.675	AK
J. S.	.975	.885
J. R.	.600	.678
R. J.	.618	.651
G. B.	.765	.810
W. M.	.714	AK
A. M.	.480	.582
S. D.	AK	1.002
R. G.	.705	.933
M. M.	.696	.600

Table 18 (continued)

Average Foot Movement Time, in Seconds
Two Trials - 10 Tries per Trial

A/B = Accelerator to Brake F/C = Firewall to Clutch
A/K = Above Knee Amputee - no data taken

Amputees

Subject	Movement	
	A/B	F/C
D. D.	AK	.738
C. M.	AK	.702
C. P.	.840	.999
L. P.	.720	AK
R. R.	.780	.765
R. D.	.618	.720
A. P.	.660	.738
R. L.	.816	.750
G. V.	AK	.789
T. B.	.840	.999
S. J.	.450	.660
J. L.	AK	.897
H. P.	.711	.630
R. S.	AK	.627
J. A.	AK	.720
M.C.	AK	.666
Mean ± S. D.	.716 ± 121	.753 ± .124

Note: The difference between the values for the laboratory staff and the amputees are significant ($p < .01$) for both A/B and F/C movements.

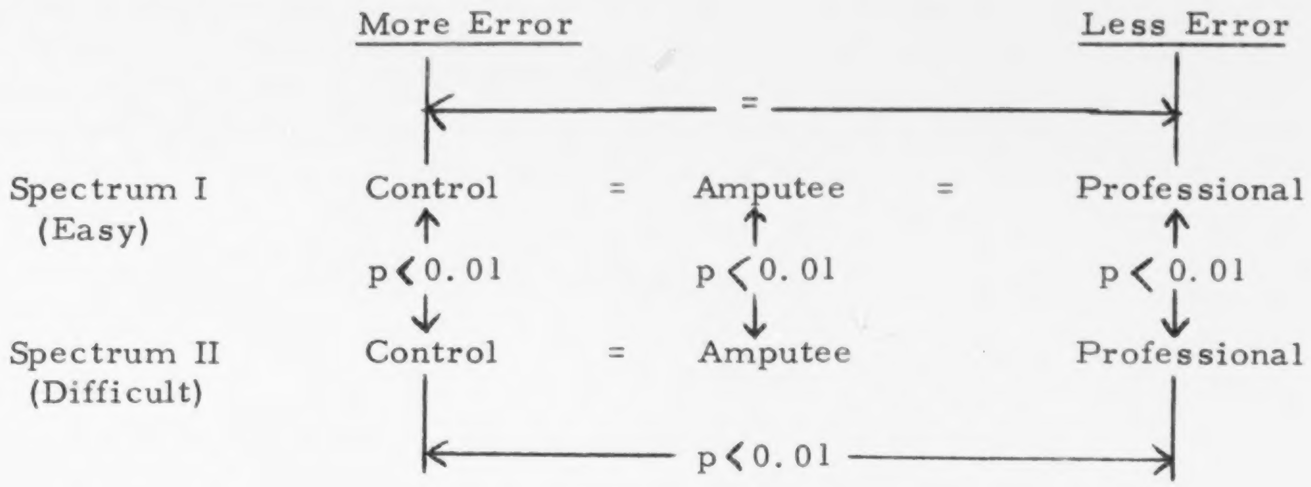
D. Summary of Experimental Results

An experiment was performed to determine whether performance would be different in a simulated driving situation between amputees and non-impaired drivers. The simulator used was of the same size as the interior of standard vehicle cabs and also allowed for adjustability of the seat to ensure operator comfort. The non-impaired drivers consisted of two equal groups of 20 subjects each; those who were commercial truck drivers, and those who were non-commercial drivers. The latter group is referred to as the control condition on group. The amputee group was made up of 80 drivers who had either an upper or a lower extremity amputation but in all cases only one limb was involved. Anthropometrically, the non-impaired subjects differed from the amputees in that they were considerably younger and taller. If the groups were controlled for age, almost all of the anthropometric differences would be removed.

Only two components of the overall driving task were studied: (1) directional control or steering, and (2) braking. The steering task involved tracking a 0.25-inch wide dot which traversed an oscilloscope face horizontally. The control follower which the subjects regulated by turning an ordinary steering wheel was a vertical line approximately 0.04 inches wide and spanned the width of the scope face. The object of the tracking task was to keep the follower and target dot in coincidence. The difficulty of the tracking task was varied by changes in either the amplitude and frequency of the moving target or the gain and mechanical impedance of the steering wheel. Two levels of difficulty in tracking were chosen and arbitrarily referred to as Spectrum I (easy tracking task) and Spectrum II (difficult tracking task). Error scores which were the distance between the follower line and target dot as well as describing functions were computed for each subject.

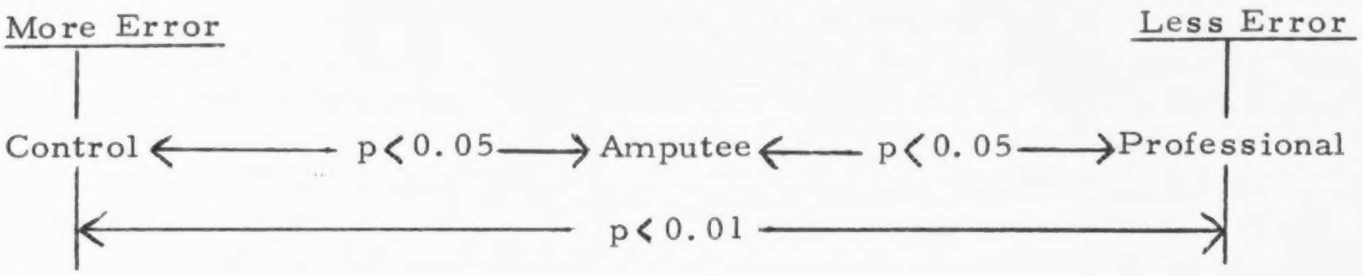
The braking task involved measuring the speed of movement of the subject's left foot from the fire wall of the cab to full depression of the clutch pedal and subject's right foot from the accelerator to deflection of the brake pedal. In this task only 36 amputee subjects and 7 members of the laboratory staff were tested.

In the steering task error averages for each group were compared sequentially. The results showed no significant differences between any of the groups on the easy tracking task. The professional drivers, however, tended to make fewer errors than the control subjects on the difficult task. The amputee group tended to perform at a level that was statistically equal both to the professional and the control groups. All groups performed more poorly on the more difficult tracking task. Schematically presented the error results are:



Note: = implies no significant difference; that is, p 0.05.

When the error scores were averaged over both spectra, the control group averaged greater error than the amputees ($p < 0.05$), and the amputees averaged greater error than the professional drivers ($p < 0.05$). The controls also had significantly more errors than the professional drivers ($p < 0.01$). Schematically the results are:



The describing function data for the steering task indicated that the amputees performed qualitatively the same as the controls. Both the amputees and the controls differed systematically however from the professional drivers. A complete description of the methods used in scoring driver responses for the steering task may be found in Appendix B.

The results in the braking test showed that: (1) the lower extremity amputees were slower than normals, and (2) while using the impaired limb, above-the-knee amputees were generally much poorer in operating foot pedals as might be expected.

Very extensive measurements were made of each subject relating to body size, structure and composition. The statistical analyses of the data revealed few significant differences between the groups studied.

Most of those observed were slight and were probably related to age. In the interpretation of the performance results from the driving simulator for the three groups it can be concluded that the upper and lower extremity amputees, compared to the control subjects, were essentially the same in their anthropological and morphological characteristics.

VIII. DISCUSSION AND INTERPRETATION OF FINDINGS

A. Validity of the Simulation Study

The use of driving simulators to study driver behavior is a widely used practice. The validation of such studies for predicting on-the-road performance however is seldom satisfactorily documented. Extensive research in simulators and on-the-road studies have shown that closed-loop describing functions derived by the two methods are generally comparable for equally demanding steering tasks. Thus far most studies have not been successful in simulating all of the decision elements of driving, probably because of the large number of cues used by the driver. This shortcoming is not relevant to the present study where only the influence of physical capabilities was under study and the influence of decision elements was deliberately minimized.

The ranges of force, speed of movement, and extent of movement in the present study include those generally encountered in private and commercial vehicles at ordinary driving speeds. Performance was observed to change in all groups as the task was made more difficult. The describing functions changed, demonstrating that either the task demands were such as to require the driver to change his tactics, or that the demands exceeded his physical capabilities to maintain linearity. Nonlinearity was observed as a function of gain for all groups, not just for the impaired. The professional drivers tended to perform better than either the controls or amputees. This finding may represent a difference in "skill", or tactics, rather than anthropometric differences. Although the evidence is not conclusive it suggests that steering "skill" is a real talent which characterizes professional drivers. Among the non-professional drivers studied there was no evidence that unilateral amputation adversely affects steering performance.

The relatively small portion of total error for all groups, not ascribable to linear operations, is consistent with the small remnant power found by other investigators using trained subjects. Although it remains to be verified, it is our opinion that the describing function differences between groups can be attributed primarily to small differences in the time constants of the lead-lag adjustment terms, terms for which it has been established that training exerts a major influence.

The findings for the subjects who took part of the tests tend to confirm the performance measures for the full schedule amputees. For the experimental conditions studied it is extremely difficult to differentiate the amputee group performance from that of non-amputee, non-commercial drivers. No attempt was made to analyze the steering performance of individual drivers in any of the groups, but differences in group homogeneity were not large. For all groups and all performance measures there was only a small overlap in the range of values observed.

B. Limitations of the Experimental Study

The fact that all participants in the study were licensed drivers and all were "volunteers" tends to restrict the generality of the results. Also the psychiatric interviews tended to show a high degree of motivation among the amputees. However, for the immediate objectives of this research the above factors are not serious limitations since orthopedically impaired persons who are able and willing to operate commercial vehicles in interstate commerce are also apt to be a highly motivated group.

A more serious problem may be related to the limited range of task conditions studied. Coordinated hand and foot movements were not required, for example,as in shifting gears with a foot clutch and hand shift lever; also the range of steering motions and forces were not as great as used in parking or in making very low speed turns in non-power steering vehicles. The operators were not required to utilize their prosthesis extensively or to time-share their intact extremities between two tasks. The turning on of windshield wipers or using the prosthesis while steering with the intact limb might be expected to be more demanding for an above the elbow amputee than for a non-amputee. Also, requiring visual guidance of the prosthesis to the switch at a time when the visual system is already overloaded might be difficult. However, several missing fingers or even a below knee amputation should not influence performance during such a maneuver. In general, trained subjects soon learn to adjust to their handicaps very effectively and safely.

C. Constraints Imposed on Driving by Various Types of Orthopedic Impairments

It was impossible in the present study to experimentally determine the interaction of a wide range of orthopedic impairments with the various elements of the driving task. Some of the likely sources of difficulty in relation to type of impairment and prosthetic countermeasures have been outlined by Torell (1966) and are discussed more fully in relation to the amputee subjects in the present study below:

1. Upper Limb Impairments

a. Finger digits

Missing digits or movement deficiencies would be expected, in some instances, to interfere with the grasping of a control device. Unless the index finger or thumb are involved, the ability to drive should not be adversely affected in properly designed vehicles. Control devices designed for safe operation with gloves worn by a wide range of the driving public, for example, present no problem to a person with only minimal hand function. Every individual, whether impaired or not, should learn to operate all of the controls required for safe driving before setting the vehicle in motion. Although this ability and/or knowledge can be checked at the time of licensing, it would seem appropriate to also require that certain safety design standards permit minimal functional capability of the hand.

b. Unilateral amputation

A below the elbow (BE) amputation properly fitted with prosthesis can be used to steer a vehicle at road speeds or during parking maneuvers if the vehicle is equipped with power steering. Limited experiments showed no difference in performance between one hand steering and one prosthesis (BE) steering. If the vehicle must be steered by the intact limb while the prosthesis is used to manipulate other controls (shift lever, light switch, etc.) in some cases an additional visual function may be required. The lack of tactile perception and constraints on gripping while using a prosthesis presents a difficulty to the amputee when vision is obstructed. This problem is identical in some respects to that of the unimpaired person driving an unfamiliar vehicle (e.g., he must look for the light switch rather than find it by feel). Again, control design and familiarity with the layout of the equipment can compensate for the (BE) amputee's difficulty.

The amputee without a prosthesis can be expected to have varying degrees of capability depending upon the functional capacity of the stump and the vehicle design.

The above elbow (AE) amputee has a more complex prosthesis and often has limited reach and strength even when well fitted. Problems can be anticipated in the use of ancillary control devices while steering with the intact limb. If all such controls are grouped so that the intact limb is used to manipulate them while steering with the prosthesis it would seem to be appropriate to license the individual upon demonstration of such ability.

c. Bilateral amputation

The number of bilateral amputee drivers, or those with impairment of both arms, who seek employment as motor vehicle operators is probably small. The number of such individuals capable of demonstrating safe operation of a vehicle, unless specially equipped, hardly warrants specific regulations. Again, ability to meet the task requirements, particularly simultaneous operation of ancillary controls during steering and braking maneuvers, should govern licensing. To facilitate the administration of the licensing process such individuals might be deprived of the normal licensing route, but a recourse should be provided for the exceptional individual well able to meet customary driving performance standards.

2. Lower Limb Impairments

a. Left leg impairments

Vehicles equipped with automatic transmission, a hand operated parking brake and light dimmer switch can be operated equally well by the unimpaired or by left leg impaired drivers. Below the knee (BK) amputations properly fitted with prostheses are able to operate foot dimmer switches and parking brakes satisfactorily. Special designs might be required for such operation with an above the knee (AK) prosthesis.

Entrance and egress from the vehicle may be a problem for lower limb amputees, but this also might be difficult for the extremely obese driver.

b. Right leg impairments

Below the knee amputees with prosthesis should not represent any special hazard in automatic transmission equipped vehicles. In vehicles equipped with hand operated accelerator and brakes both BK and AK amputees may be capable of safe operation provided that upper extremity function is normal.

c. Bilateral impairments

Bilateral lower extremity amputees will generally require hand operated controls. Although many hand controlled vehicles are in use, the vehicle designs and training programs for such users have been largely neglected.

3. Impairment of Movements of Neck and Trunk

The use of shoulder harnesses has imposed some design difficulties on the vehicle manufacturer, especially if they neglect the need for trunk flexion by the driver. This problem is now being studied for a wide range of drivers in size and with certain physical limitations. Neck movements remain important for visual search, particularly at intersections or when backing. Ability to see the rear-view mirror and each side window would appear to be a minimum functional requirement.

IX. GENERAL SUMMARY OF THE PROJECT

A. Purpose of the Project

The Interstate Commerce Act has placed severe restrictions upon commercial driving by amputees and others with physical impairments (see subparagraph (1), Section 204(a), Interstate Commerce Act /49 U. S. C. 304/). Although objective evidence supporting the need for such restrictions has been lacking, attempts to modify the law for the physically impaired drivers who are able to pass conventional licensing road tests have not been successful.

At the present time there is great concern on the part of licensing authorities in each state, as well as medical and public health officials, in regard to the physical examination and licensing of all classes of drivers, of which amputees constitute one category. Adequate criteria for disqualification have not been worked out. This applies not only to major disease areas such as epilepsy, diabetes and heart disease to mention only a few, but also to amputations and related physical impairments. The Vocational Rehabilitation Administration has been especially concerned with this problem not only because of the lack of sufficient data in regard to commercial driving by the physically impaired, but also because a large number of persons may be unfairly deprived of opportunities for employment.

Information relating to the ability of amputees to drive motor vehicles is a basic requirement in clarifying some of the problems involved in the rather arbitrary elimination of such drivers from operating equipment in interstate commerce. The objectives of the present project were to document the driving experience of the physically impaired and to test whether amputees differ from non-amputees in the operation of a simulated vehicle.

The approach to achieving the first of these objectives involved a survey of the literature related to licensing and a study of the driving experience of the physically impaired. Special attention was given to (1) determining the licensing requirements for the physically impaired in the 50 states, (2) ascertaining what data are routinely collected, (3) estimating the accident experience of the impaired, and (4) an evaluation of the driving records of the known physically impaired persons registered in Massachusetts. In this last phase, attention was given to (a) age, (b) type of impariment, and (c) frequency and class of accident, legal citations, and costs.

The second objective of the project involved an experimental analysis of simulated driving performance by the physically impaired. An apparatus was developed which would simulate the geometry and varied functions of commercial vehicle controls and workspaces. The apparatus provided for controlling and measuring stimulus inputs and driver responses under controlled laboratory conditions. The dynamics of the apparatus are variable in order to permit testing for a wide range of simulated vehicle characteristics.

B. Literature Survey

In a detailed review of the literature, a large number of studies were reviewed and abstracted. It became apparent that no truly comprehensive analysis of existing information has been published. Also, most of the reports were not experimental, and were unsuitable for appraising the driving ability of amputees and others with physical abilities. In regard to the driving laws of the states, wide variations were found. Some states had almost no regulations at all, while in others regulations were not standardized. In a few instances driver training programs have been developed, but general supervision was essentially lacking. Only a few states have collected data relating to the physically impaired. In general, the reports did not provide adequate information for making an appraisal of the accident experience of drivers with physical handicaps.

C. Evaluation of Driving Records of the Physically Impaired

A comprehensive study was carried out relating to the operation of private motor vehicles by physically impaired drivers in the Commonwealth of Massachusetts. In this study, the data showed a lower rate of involvement for disabled drivers versus their non-disabled counterparts. The ratio was approximately 2. 1; that is, the non-disabled control group sustained approximately twice as many accidents and were charged with approximately twice as many non-accident violations as the disabled. This ratio appeared to remain constant regardless of the variable considered. The costs of accidents charged to the non-impaired were twice as great as those charged to the impaired. Age did not appear to be a variable differentiating groups with or without citations for accidents or non-accident incidents.

The literature reviewed, in general, dealt with studies of impaired persons licensed to operate private automobiles. The same was true for the Massachusetts study. There is no evidence that these data should or should not be extrapolated to commercial drivers operating commercial vehicles such as tractor-trailers, buses, or other special vehicles, that differ in engineering design from conventional passenger cars.

D. Experimental Evaluation of Amputee Drivers

A vehicle simulator was constructed for comparing selected performance measures of amputees with those of commercial truck drivers and with non-impaired, non-commercial drivers. Experiments for this project were limited to a study of the physical components of steering and braking. A specific steering task was used and the gain and mechanical input impedance of the steering wheel varied over a wide range. Error scores and describing functions were derived for each steering condition studied. Speed of movement from accelerator to application of a brake force was the performance measure for the braking tests.

A total of 100 persons were studied. Twenty were non-impaired, non-commercial vehicle drivers, 20 were non-impaired commercial vehicle drivers, and the remainder were amputees. Extensive physical anthropological measurements were collected for all subjects. All amputees also received thorough clinical interviews.

1. Results from Clinical Interviews

One major finding of the clinical interviews was the nearly universal presence of chronic depression. Many had intense feelings and attitudes which had not been worked out or resolved. The evidence was that the rehabilitation process had been mostly concentrated upon the problem of physical restoration. Such areas as vocational rehabilitation, retraining, continuing education, or advancing higher education in the postwar amputee seemed limited. What seems to pass for "rehabilitation" in the non-physical area appeared to be perfunctory and in some instances there was evidence of outright neglect. Hostility to both public and private rehabilitation agencies, though not universal, was common. The resources of the community did not seem to be mobilized in the interests of "total" rehabilitation.

Another apparent trend was that amputations do not seem to be randomly distributed among the hazard-exposed group. Furthermore, a surprising number of veterans in this sample had nonservice-connected amputations, and of these, an unexpected number had parents or near relatives who also had amputations. After taking account of distortions of report, the general pattern seemed to be that subjects have had, and are experiencing, more than their share of life-long stress. Only a few were interested in interstate commercial driving. Two of these were actually operating commercial vehicles illegally.

2. Results of the Experimental Tests

The results of the steering performance tests may be briefly summarized as follows:

a. Both the amputees and the non-amputees showed poorer performance in the more complex tasks or when the requirement for physical forces was increased.

b. The commercial non-impaired drivers performed better than the amputees or the non-impaired, non-commercial drivers.

c. The amputees performed as well or better than did the non-impaired, non-commercial drivers.

2. The results of brake pedal tests indicated that lower extremity amputees required longer time to operate the brake than did non-impaired persons. As would be expected, above the knee amputees were generally unsuccessful in operating pedals using the impaired limb.

3. The findings in regard to anthropometric tests revealed no significant group differences except for slight ones which may have been age related. Also in regard to data from the performance tests for the three groups no significant differences were observed which could be attributed to body size or body composition. Thus, all groups appeared to be essentially similar in their anthropological and morphological characteristics. The extensive results obtained from the anthropometric measurements may prove to be of value to the designers of trucks for all drivers and in the preparation of special devices for those physically impaired.

E. Conclusions

1) There is no evidence from this study that orthopedically impaired persons, who are able to pass conventional driver licensing road tests, have greater accident frequencies than do unimpaired ones. 2) The experiments conducted as part of this project support the view that, with appropriate power assists, unilateral orthopedic impairment should not necessarily impair driving performance. This was found to be especially true of those with unilateral upper extremity amputations. However, the frequent unresolved emotional problems of the amputees studied in this project suggest that psychological screening before licensing might be more productive than screening on the basis of orthopedic impairment alone. Moreover, studies of both professional and private drivers with poor accident records have shown that they often use alcohol excessively, have poor attitudes and social adjustments, or they are emotionally disturbed. The above factors appear to be much more important than conditions related to physical disease or orthopedic impairments per se. 3) It would appear to be in order therefore to reappraise the driving abilities of those with certain kinds of amputations in the light of each individual's overall ability to operate vehicles in interstate commerce rather than arbitrarily prejudge their ability in negative terms. 4) Furthermore, the orthopedically impaired person usually has a high degree of motivation to succeed as a safe driver. They tend to try harder, to be more careful, and to have as good or better safety records than the physically unimpaired ones.

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Appendix A. Driving Questionnaire and Interviewing Schedule

DRIVING QUESTIONNAIRE

I. How old were you when you first received your driving license? _____

II. Was your first license a restricted one? If so, in what way?
A. Yes _____
B. No _____

III. How long have you been driving a car? _____

IV. Do you like to drive? Specify why
A. Yes _____
B. No _____

V. Approximately how many miles do you drive in a year? _____

VI. What kind of driving do you do?
A. Rural _____
B. Urban _____
C. Suburban _____
D. Combination with more mileage in
  1. City _____
  2. Country _____
  3. Suburban _____

VII. Do you have any problems in handling your own car? (In relation to your own physical disability)
A. Yes _____

Specify
B. No _____

VIII. How is your present driving record?
A. No accidents _____
B. Major accidents _____
  Give frequency _____
C. Only traffic violations _____
  Give frequency _____
D. No traffic violations _____
E. Other comments _____
  Give frequency _____

IX. Is there any difference between your driving record before your illness or accident and your present record?
A. Yes _____

Specify in what way record is different
B. No _____

X. If present record is better, then what was earlier record like in relation to

A. Ordinary traffic violations

____

B. Accidents requiring notification to registry of motor vehicles

____

XI. What is your opinion based on your own experience of the other drivers in this geographical area?

A. Excellent ____________
B. Good ____________
C. Fair ____________
D. Poor ____________
E. Very poor ____________

XII. What is your opinion based on your own experience of the other drivers in other geographical areas?

Specify opinion and area

A. Excellent ____________
B. Good ____________
C. Fair ____________
D. Poor ____________
E. Very poor ____________

XIII. Do you know anything about the instrumentation of the following commercial vehicles?

A. Yes ____________
B. No ____________

XIV. Have you ever driven a commercial vehicle?

Specify what kind and how long

A. Yes ____________
B. No ____________

XV. Do you think you could learn to drive any or all of these commercial vehicles?

Specify which ones

If no, why not?

A. Yes ____________
B. No ____________

XVI. Would you like to have a job of this kind?

A. Yes ____________
B. No ____________

XVII. What is your reaction to anyone with your particular physical limitations driving a commercial vehicle?

____

XVIII. Do you ever use your car for commercial purposes?
A. Yes ________
B. No ________

XIX. What kind of license do you have now? ________

INTERVIEWING SCHEDULE
Section 1

I. Identifying information
- A. Name ________
- B. Address ________
- C. Telephone number ________
- D. Birthdate ________
- E. Marital status
  - 1. Single ________
  - 2. Married ________
    Date of marriage ________
  - 3. Widowed ________
    Date of wife's death ________
  - 4. Divorced ________
    Date of divorce ________
  - 5. Separated ________
    Date of separation ________
- F. Previous marriages
  - 1. Date of marriage ________
  - 2. Date of divorce ________
  - 3. Date of wife's death ________
- G. Original family structure and constellation
  - 1. Brought up by both parents
    a. Yes ________
    b. No ________
    If no, brought up by whom ________
  - 2. Siblings

	Male	Female
Older	____	____
Younger	____	____

- H. Father's occupation ________
- I. Nature and date of occurrence of similar injury, amputation, or illness of any relative or friend (give specifics)
- J. Date and nature of previous serious accident or illness of participant

Identifying information (continued)

K. Structure and constellation of procreative family
  3. Chronological age and sex of children

Wife's birthdate ______________________________
Wife's occupation ______________________________

II. Participant's response to research project
  A. School achievement (List last grade completed)
    1. Grade school and Jr. High School 1-10__________
    2. High School 9-12__________
    3. College 1-4 __________
  B. Special training
    1. Graduate education
      a. Area of interest______________________________
      b. Number of years attended ______________________
      c. Degree received ______________________________
    2. Technical school
      a. Area of interest______________________________
      b. Number of years attended ______________________
      c. Diploma or certificate received________________
    3. Other (specify)

  C. School
    1. Specific satisfactions

    2. Specific dissatisfactions

  D. Family's expectations for academic achievement

  E. Further educational plans for self development
    1. Yes _______ No _______
    2. Type of plan
      a. Formal education ______________________________
      b. Technical ______________________________
      c. On the job ______________________________
      d. Other ______________________________
    3. Subject or field of interest
    4. Method of financing
      a. Personal savings ______________________________
      b. Family ______________________________
      c. Personal loan ______________________________
      d. Scholarship or fellowship______________________
      e. State educational funds ______________________
      f. OVR ______________________________
      g. Other Federal funds (specify) ________________
      h. Other means (specify) ________________________

Section 2

I. Trauma

- A. Occurrence of accident of illness
  - 1. Date ______________________________________
  - 2. Circumstances
- B. Circumstance occurring at the time of injury, accident or illness (Be specific)
  - 1. Physical trouble
  - 2. Emotional upset
  - 3. Difficulties with or in family
  - 4. Difficulties with someone else
  - 5. Other (specify)
- C. Premonitory feelings (Give details)
  - 1. Generalized premonition
  - 2. Specific premonition
  - 3. None
- D. Explanation of causes of accident (Give details)
  - 1. Own responsibility
  - 2. Omission of acts
  - 3. Omission of acts of others
  - 4. Behavior which never should have occurred
  - 5. Chance or luck
  - 6. Punishment
  - 7. Other (specify)

II. The experience of amputation

- A. Length of time between accident or illness and amputation
- B. Phantom limb experiences (Material given by interviewee should be verbatim)
  - 1. When they occurred
  - 2. Description
  - 3. Length of time they lasted
  - 4. Present now
    - a. Yes ______ No ______
    - b. If yes, give description of present experience

III. Experience of hospitalization

- A. Length of hospitalization ______________________________
- B. Hospital services seeming particularly helpful (Give details)
  - 1. Doctors
  - 2. Nursing
  - 3. Occupational therapy
  - 4. Volunteer
  - 5. Recreation
  - 6. Social service
  - 7. Other (specify)

Experience of hospitalization (continued)

C. Discharge planning
1. Originated by
a. Participant ________
b. Doctor with participant's comfortable cooperation ________
c. Doctor or hospital personnel before participant felt ready ________
d. Other ________
2. Achieved
a. Without help ________
b. With help from
(1) family ________
(2) social service ________
(3) combination hospital personnel plus family ________
(4) other ________
D. Physical condition at time of hospital discharge
1. Self care
a. Complete ________
b. Needed help ________
2. Motility
a. Able to get around along ________
b. Able to get around with help ________
c. Not able to move around at all ________
3. Prosthesis (Give details)
a. Kind of Prosthesis ________
(1) able to use ________
(2) unable to use ________

IV. Emotional experience
A. Participant's depression following injury, accident or illness
1. Description of feelings (Give details)
2. Extent to which feelings disabled participant
3. Participant's method of dealing with feelings of depression
4. Circumstances or events that alleviated depression (Give details)
a. Time they occurred ________
b. Extent of help ________

Section 3

I. Civilian work experience
A. Nature of last job held prior to military experience (Give deatils)
1. Description of job
2. Length of time job was held
3. Feelings about job
a. Satisfactions
b. Dissatisfactions

Civilian work experience (continued)

- 4. Relationship with superior
- 5. Relationship with fellow employees
- 6. Plan for continuing this occupation after military service
  - a. Yes ______ b. No ______

II. Military experience

- A. Assignment (Give details)
  - 1. Description of assignment
  - 2. Same as civilian occupation
    - a. Yes ______ b. No ______
  - 3. Length of assignment ______
  - 4. Satisfactions and dissatisfactions
  - 5. Relationship to immediate superior
  - 6. Relationship to fellow servicemen
  - 7. Plan for continuing this occupation after military service
    - a. Yes ______ b. No ______

III. Work experience following accident

- A. Present occupation
  - 1. Description of job ______
  - 2. Length of time on this particular job ______
  - 3. Satisfactions and dissatisfactions
  - 4. Relationship to immediate superior
  - 5. Relationship to fellow employees
- B. Effect of accident or illness on profession or vocation
  - 1. No effect ______
  - 2. Modification of production in profession or vocation ______
  - 3. Forced to change job ______
  - 4. Other details ______
- C. Vocational training following accident, illness or injury (Give details)
  - 1. Yes ______
  - 2. No ______
    - a. Vocational rehabilitation was offered but refused ______
    - b. Vocational training was not recommended ______

IV. Participant's activity

- A. Personal care
  - 1. Provided by self ______
  - 2. Provided by others (specify) ______
- B. Motility
  - 1. Able to get around alone ______
  - 2. Able to get around with help (specify) ______

V. Participant's role in family

- A. Responsibility for supporting family
  - 1. Present
    - a. Total ______
    - b. Partial ______

Participant's role in family (continued)

c. None ________________
If partial or none, give details of effect
of accident or illness on earning power
2. Past
a. Total ________________
b. Partial ________________
c. None ________________
B. Major family decisions

1. Present	2. Past
a. Made by self (give examples) ______________________________ ______________________________	a. Made by self (give examples) ______________________________ ______________________________
b. Made with wife ____________	b. Made with wife ____________
c. Made by wife ______________	c. Made by wife ______________

C. Decisions regarding children
1. Made by self (give examples) ______________________________________
____
2. Made in cooperation with wife __________________
3. Made by wife ________________
D. Participation in household chores

	With use of prosthesis	Without use of prosthesis
1. Inside repair work	______	______
2. Dishes	______	______
3. Cleaning inside of house	______	______
4. Outside repair work on house	______	______
5. Care of lawn	______	______
6. Repair car	______	______
7. Other (specify)	______	______

E. Difference in role due to accident or illness
1. Yes ______ 2. No ______
If yes, give specific details

VI. Emotional relationships
A. Wife
1. Effect of accident or illness
a. Depression
(1) Extent
(2) Degree
(3) Source of help for her
b. Other effects (specify)

2. Effect of illness or injury on marital relationship
a. Sexual adjustment problems
(1) Nature of problems
(2) Date of occurrence
(3) Length of time they lasted
(4) Source of help
(5) Presence of these same problems before accident
Yes ________ No ________

Emotional relationships (continued)

(6) Problems attributed to accident or illness
(a) By wife Yes ______ No ______
(b) By participant Yes ______ No ______
3. Change in wife's attitude following injury or illness
a. Yes ______ No ______
b. If yes, specify
B. Children
1. Effect of accident or illness
(1) Yes ______ No ______
(2) If yes, give details
2. Participation with children in any activities (give details)
C. Friends
1. Effect of accident or illness
a. Too much sympathy ______________________
b. Too little sympathy ______________________
c. No change in relationship or attitude ______
d. Other problems

VII. Social, community and recreational activity
A. Social activity
1. Place
a. Largely in the home ______________________
b. Largely outside the home ________________
2. List three favorite social activities
____
____
____
B. Community activity
1. Participation
a. Yes ______ No ______
b. If yes, list three __________________________
____
____
2. Memberhip in amputee association
a. Yes _______ No ______
b. Active membership Yes ______ No ______
C. Recreational activity
1. Participation
a. Yes ______ No ______
b. If yes, list three
____
____
________________________________+
D. Desire to increase activities
1. Yes ______ No ______
2. If yes, in what direction (specify)

Section 4B

(For single men)

I. Housing conditions
  A. Type

	Own	Rent
1. Room	________	________
2. Apartment	________	________
3. House	________	________

  B. Suitability of housing arrangement
    1. Presence of facilities adapted to physical disability
      a. Yes ________ b. No ________
    2. Satisfaction with housing arrangement
      a. Yes ________ b. No ________
      If no, give details of problems

  C. Living with
    1. Self ________
    2. Parents ________
    3. One parent (specify) ________
    4. Siblings (specify) ________
    5. Other relatives (specify) ________
    6. Other (specify) ________________

II. Participant's activity
  A. Personal care
    1. Provided by self ________
    2. Provided by others (specify) ________
  B. Motility
    1. Able to get around alone ____________
    2. Able to get around with help __________
      (specify) ________________________

III. Participant's role in family
  A. Responsibility for supporting family

1. Present	2. Past
a. Total ______	a. Total ______
b. Partial ______	b. Partial ______
c. None ______	c. None ______

      If partial or none, give details of effect
      of accident or illness on earning power

  B. Major family decisions

1. Present	2. Past
a. Made by self (give examples)	a. Made by self (give examples)
____________	____________
____________	____________
____________	____________

Participant's role in family (continued)

b. Made with other members of household ________	b. Made with other members of household ________
c. Made by other members of household ________	c. Made by other members of household ________

C. Participation in household chores

	With use of prosthesis	Without use of prosthesis
1. Inside repair work	________	________
2. Dishes	________	________
3. Cleaning inside of house	________	________
4. Outside repair work on house	________	________
5. Care of lawn	________	________
6. Repair car	________	________
7. Other (specify)	________	________

D. Difference in role due to accident or illness
    1. Yes ________ 2. No ________
    If yes, give specific details

IV. Emotional relationships
  A. Mother
    1. Effect of accident or illness
      a. Depression
        (1) Extent
        (2) Degree
        (3) Source of help for her
      b. Other effects
    2. Change in mother's attitude following accident or illness
      a. Yes ________ b. No ________
      If yes, specify
  B. Father
    1. Effect of accident or illness
      a. Depression
        (1) Extent
        (2) Degree
        (3) Source of help for him
      b. Other effects
    2. Change in father's attitude following accident or illness
      a. Yes ________ b. No ________
      If yes, specify
  C. Sibling (if appropriate)
    1. Effect of accident or illness
      a. Depression
        (1) Extent
        (2) Degree
        (3) Source of help for sibling
      b. Other effects

Emotional relationships (continued)

2. Change in sibling's attitude following accident or illness
    a. Yes ________ b. No ________
        If yes, specify

D. Other family members (specify)
    1. Effect of accident or illness
        a. Depression
            (1) Extent
            (2) Degree
            (3) Source of help
        b. Other effects
    2. Change in family member's attitude following accident or illness
        a. Yes ________ b. No ________
            If yes, specify

V. Social, community and recreational activity
    A. Social activity
        1. Dates
            a. Often ________
            b. Seldom ________
            c. Never ________
        2. Girl friends
            a. Steady ________
            b. Many ________
            c. Few ________
        3. Expectation of marital plans
            a. Yes ________ b. No ________
                If no, for what reason
    B. Community activity
        1. Participation
            a. Yes ________ No ________
                If yes, list three
                ____
                ____
                ____
        2. Membership in amputee association
            a. Yes ________ No ________
            b. Active membership Yes ______ No ______
    C. Recreational activity
        1. Participation
            a. Yes ________ No ________
            b. If yes, list three
                ____
                ____
                ____
    D. Desire to increase activities
        1. Yes __________ No __________
        2. If yes, in what direction (specify)

Section 5

I. Participant's present feelings about accident in relation to life
    A. Over-all view
        1. Concrete

        2. Emotional

II. Description of way interviewee acted in this situation

III. Interviewer's reaction to interviewee

Appendix B. Measurement of Time-Variable Describing Functions

Time variations in human describing functions have been observed for several tracking tasks (see for example Garvey and Mitnick, 1957, and Cacioppo, 1956). After an extensive review of the literature McRuer and Krendel (1957) conceded that time-variation could have caused much or all of the remnant observed in numerous other tracking studies. Therefore, measurement of time-variation in describing function parameters may offer significant improvement in characterizing human performance. Sheridan (1960a) has described several situations where such information would be useful, documented theoretical considerations in measuring time-variation, developed an inexpensive method for such measurements during laboratory tracking experiments, and reported several experimental observations of time-variation.

Sheridan's method of computing time-variable describing functions depends upon the use of orthogonal target inputs, and the multiplication of the human operator's output response by orthogonal components of the target inputs. A block diagram of elements used in this technique appears in Figure 17. The target input, r(t), is the sum of n sinusoids of amplitude A_i and frequency w_i, which are relatively prime-to-one-another so as to be random-appearing.

$$(1) \quad r(t) = \sum_{i=1}^{n} A_i \sin w_i t$$

For a first order control system (such as was used in the experiments) the operator's output, c(t), for perfect tracking would be equivalent to the derivative of the target input.

$$(2) \quad c(t) = \frac{dr(t),}{dt} \quad \text{or } r(t) = \int c(t)dt$$

However, since a random appearing target was used, perfect tracking was impossible. The operator's output under such conditions may be characterized as:

$$(3) \quad c(t) = \sum_{i=1}^{n} \frac{kA_i}{w_i} \cos(w_i t + \theta_i) + n(t)$$

where k represents a conversion factor relating display amplitude ratio to control deflection amplitude, 0 represents the phase angle, and n(t) represents random noise.

Sheridan multiplied the control system movements by separate orthogonal components (sine and cosine functions) of each input frequency. The multiplications were performed by impressing positive and negative values of these components across potentiometers geared to the control system. Thus, each potentiometer wiper voltage was proportional to the product of operator output and one of the orthogonal components of one of the target input frequencies. For example, if R_1 represents the product of c(t) and one of the input sinusoids.

$$(4) \qquad c(t)\cdot gA_1 \sin w_i t = gA_1 \sin w_1 t \left[\sum_{i=1}^{n} \frac{kA_i}{w_i} \cos(w_i t + \theta_i) + n(t) \right]$$

where gA_1 represents the amplitude of the signal impressed on this multiplication potentiometer. By application of appropriate trigonometric identities this equation may be rearranged as follows:

$$(5) \qquad R_1 = gA_1 \sin w_1 t \left[\frac{kA_1}{w_1} (\cos w_1 t \cos \theta_1 - \sin w_1 t \sin \theta_1) \right]$$

$$+ gA_1 \sin w_1 t \left[\sum_{i=2}^{n} \frac{kA_i}{w_i} (\cos w_i t \cos \theta_i - \sin w_i t \sin \theta_i + n(t) \right]$$

$$(6) \qquad R_1 = \frac{gkA_1^2}{2w_1} (\sin 2w_1 t \cos\theta_1 - \sin\theta_1 + \cos 2w_1 t \sin\theta\ )$$

$$+ \sum_{i=2}^{n} \frac{gkA_1 A_i (\sin w_1 t)}{w_i} \cdot \left[\cos w_i t \cos\theta_i - \sin w_i t \sin\theta_i + n(t) \right]$$

$$(7) \qquad R_1 = \frac{-gkA_1^2}{2w_1} \sin\theta_1 + \frac{gkA_1^2}{2w_1} \sin(2w_1 t + \theta\ ) + \ldots\ldots$$

If these products are averaged over a time interval approaching infinity, the averages of those portions containing orthogonal products or sinusoidal time functions will approach zero. The only remaining term in equation (7) is then,

$$(8) \qquad \tilde{R}_1 = \frac{-gkA_1^2 \sin\theta_1}{2w_1}$$

$\sim$= smooth or filtered function

Similarly, if I_1 represents the product of c(t) and the cosine of one of the input sinusoids,

$$(9) \quad I_1 = \frac{+gkA_1^2}{2w_1} \cos \theta_1 + \frac{gkA_1^2}{2w_1} \cos (2w_1 t + \theta_1)$$

$$+ \sum_{i=2}^{n} \frac{gkA_1 A_i(\cos w_1 t)}{w_i} \left[\cos w_i t \cos \theta_i - \sin w_i t \sin \theta_i + n(t)\right]$$

which may also be averaged to yield,

$$(10) \quad \bar{I}_1 = \frac{+gkA_1^2}{2w_1} \cos \bar{\theta}_1$$

$\bar{R}_1$ and $\bar{I}_1$ represent the real and imaginary terms of the wheel movement with respect to the w_1 component of the target input. Alternatively, $\bar{R}_1$ and $\bar{I}_1$ may be regarded as the product of k and the coefficients of the correlation between c(t) and the real and imaginary components of the input frequency w_1. Magnitude ($\bar{Z}_1$) and phase (θ_1) may be determined from the real and imaginary components by the relations:

$$(11) \quad \bar{Z}_1^2 = \bar{R}_1^2 + \bar{I}_1^2 = \frac{g^2k^2A^4}{4w_1^2} \sin^2 \theta_1 + \frac{g^2k^2A^4}{4w_1^2} \cos^2 \theta_1 = \frac{g^2k^2A^4}{4w_1^2}$$

$$(12) \quad \bar{Z}_1 = \sqrt{\bar{R}_1^2 + \bar{I}_1^2} = \frac{gkA_1^2}{2w_1^2}$$

$$(13) \quad \theta_1 = \tan^{-1}\left(\frac{\bar{R}_1}{\bar{I}_1}\right)$$

The same computations may be used to solve for $\bar{R}_i$, $\bar{I}_i$, $\bar{Z}_i$, or $\bar{\theta}_i$.

Since use of an infinitely long averaging time period is obviously impractical, a compromise low-pass filter is required. Sheridan used an RC lagger consisting of two cascaded lags, each with time constants of 7.2 seconds (lowest target frequency component was 0.1 cps). This filter provided good attenuation of the noise and cross products while still allowing moderate resolution of rapid time-variation in operator response characteristics.

Using a first order system, perfect tracking without phase lag requires that c(t) lead r(t) by 90. Thus, R_i would be zero and I_i would be $\frac{g_i k_i A_i^2}{2w_i}$.